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VIEWS ON SCIENCE POLICY OF THE NOBEL LAUREATES FOR 1982

HEARING

BEFORE THE

COMMITTEE ON SCIENCE AND TECHNOLOGY U.S. HOUSE OF REPRESENTATIVES

NINETY-EIGHTH CONGRESS

FIRST SESSION

FEBRUARY 23, 1983

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VIEWS ON SCIENCE POLICY OF THE NOBEL LAUREATES FOR 1982

WEDNESDAY, FEBRUARY 23, 1983

House of Representatives,
Committee on Science and Technology,
Washington, D.C.

The committee met, pursuant to call, in room 2318, Rayburn House Office Building, Hon. Don Fuqua (chairman) presiding.

Mr. **Fuqua**. The committee will be in order.

I am very pleased this morning to welcome our Nobel laureates in science for 1982.

Our hearing affords the members of Congress a unique opportunity to hear the views of that very small number of scientists who each year have been selected for the highest honor in their fields.

Based on the recommendations of scientists throughout the world, the Swedish Nobel Foundation selects each year one or two researchers who have made a clearly outstanding contribution to the advancement of science.

In recent years many Americans have been honored in this manner. In 1980 six of the eight laureates were U.S. scientists, and last year seven of the nine laureates were Americans.

However, we are well aware of the strength and vigor of science in other parts of the world. That strength is reflected in the most recent group of Nobel awards when, in addition to two Americans, two Swedish scientists and two British scientists were selected to receive the Nobel Prize.

We are delighted and honored to have with us today one of those Swedish laureates. Dr. Sune Bergstrom was recognized jointly with two other scientists for his discoveries in controlling prostaglandins, a substance found in muscle tissue. He comes to us from Stockholm where he was associated with the famous Karolinska Institute, and he has very kindly agreed to give us his views on the status of science in the world, and especially in Europe.

Dr. Kenneth Wilson received the prize in physics for his outstanding work on critical phenomena connected with phase transitions. He comes to us from Cornell University where he is professor of physics and he will discuss with the committee several issues related to science policy in the United States and in the world.

The two laureates are being joined today by another distinguished scientist who, like them, has been singled out by his fellow scientists for high honors. Dr. Frank Press was elected in 1980 by the members of the U.S. National Academy of Sciences as their president. Dr. Press has had a long and distinguished record not only as a practicing scientist, but also as science advisor to President Carter, and as a member of the National Science Board. He is an old friend of this committee, and we welcome him as well.

If agreeable, I will ask our three guests to present their opening remarks first, and, following that, we will direct questions to each of them.

I would like to ask Dr. Bergstrom to lead off.

Dr. Bergstrom, we are very pleased to have you here. We congratulate you. We are pleased to hear your comments.

STATEMENTS OF DR. SUNE BERGSTROM, NOBEL LAUREATE IN MEDICINE AND MEMBER, KAROLINSKA INSTITUTE, STOCKHOLM, SWEDEN

Dr. **Bergstrom**. Thank you, Mr. Chairman, members of the committee.

It is a great honor for me to appear here. I am especially happy as it gives me an opportunity to express my great indebtedness to your country. I did part of my graduate work here as a fellow of the Swedish-American Foundation in 1940 to 1942.

During the fifties, I was very generously supported by the international program of the National Institutes of Health, a support that was very important to my work on prostaglandins.

There are three specific interactions in biomedical research between the United States and Sweden that I think might be appropriate to review briefly.

The interest in biomedical research in Sweden was undoubtedly stimulated in the first decades of this century by the creation of the Nobel Foundation especially at the Karolinska Institute that was entrusted with the selection of the laureates.

The intention of the Swedish inventor and industrialist, Alfred Nobel, was to create prizes for outstanding scientists from any part of the world—prizes that were large enough to relieve them from personal economic problems during the rest of their lives to ensure that they could continue their work for the benefit of mankind.

At the beginning of the century, the prizes corresponded to 20 annual salaries of a university professor.

The institute also received a large private donation for support of medical research, probably larger than the research budget of any other medical school in Europe in the twenties.

The first important impact of the United States was made by the Rockefeller Foundation in supporting biomedical research in Sweden. It started in the late twenties and continued through the thirties. It consisted of approximately 90 grants and fellowships, mostly in biomedical research.

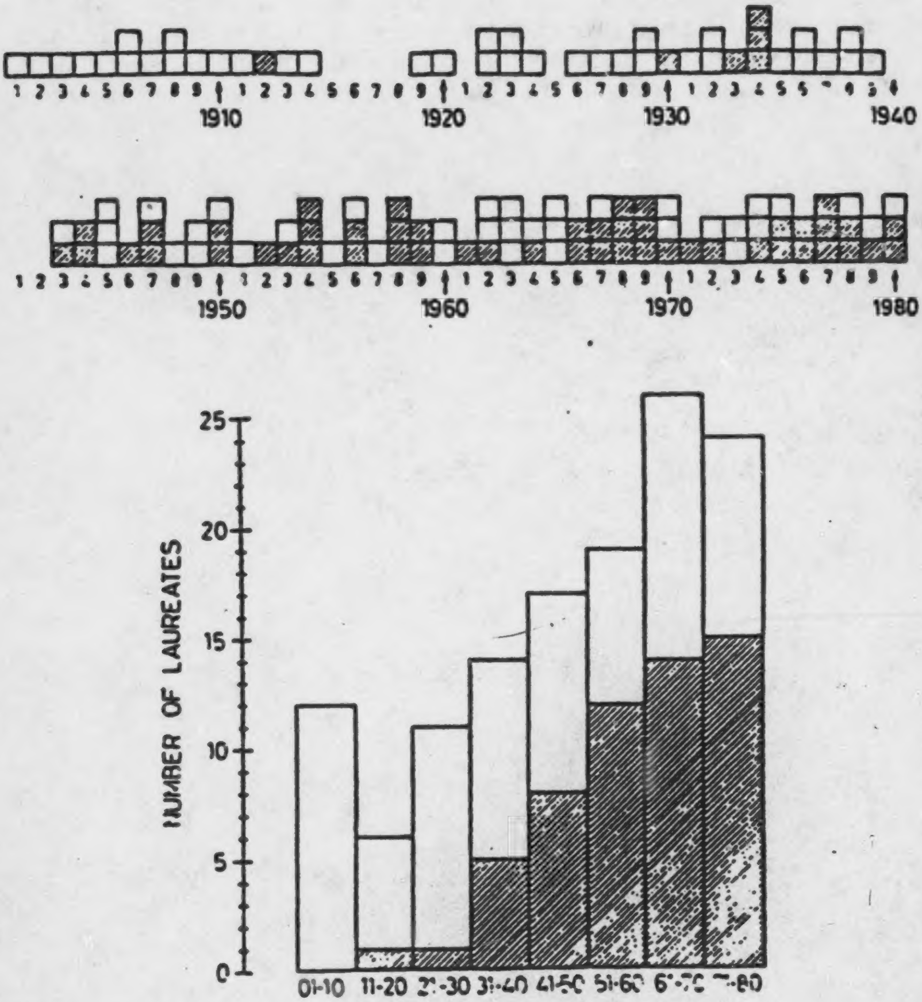
This was extremely important because in those days we didn't have research councils. More than half of them became professors and established invaluable contacts with your country.

Only relatively late, starting during and immediately after the war, did the governments in many countries become aware of the need for systematic planning of, and increased support for biomedical research and development to cope with the health problems of their countries. This led to the creation of various forms of governmental research councils that have almost completely taken over the financing of biomedical research from the pioneering private foundations.

Of course, the outstanding example of this development is the expansion of the federally supported National Institutes of Health and their extramural programs, which in 30 years have brought the biomedical research of the United States to preeminence in many fields. Many parameters can be used to demonstrate this fact, but I will only use one: the increase in the number of U.S. scientists who have received the Nobel Prize in physiology or medicine. I have a diagram of that in my paper that has been distributed.

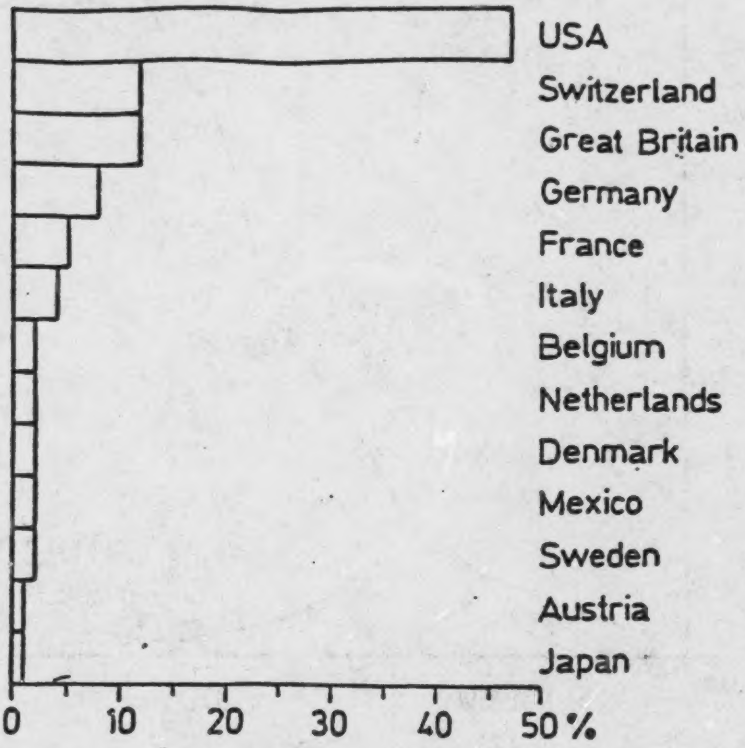
NOBEL LAUREATES IN MEDICINE OR PHYSIOLOGY

▨ FROM USA, ☐ FROM OTHER COUNTRIES



During the first two decades of this century, 1 prize out of 18 went to a part-time U.S. resident. During the last two decades, 29 out of 50 went to U.S. scientists.

A similar strong position in research and development has also been achieved by the American pharmaceutical industry. An illustration of that is given in figure 2, in which the introduction of new drugs from 1958 to 1970 is recorded, indicating that 50 percent of them originated from U.S. pharmaceutical industry, a parameter that possibly would show a less impressive picture today.



The origin of 437 new pharmaceutical chemical compounds introduced into the world market 1958 - 1970

Figure 2.

The Rockefeller Foundation discontinued its support of biomedical research after the war. At that time the National Institutes of Health started its unique support of international science. In the beginning of the sixties about $15 million were given annually for research in other countries, the only provision being that the research was judged to be of interest and possible benefit also for the American public.

Sweden was one of the countries that got much of this support and one year the support was even more than our own, newly established Medical Research Council—figure 3. This international support catalyzed a lot of governmental interest in research in many European countries and when it disappeared, it again stimulated the governments to replace the lost money and they then usually continue to increase the support to their research councils.

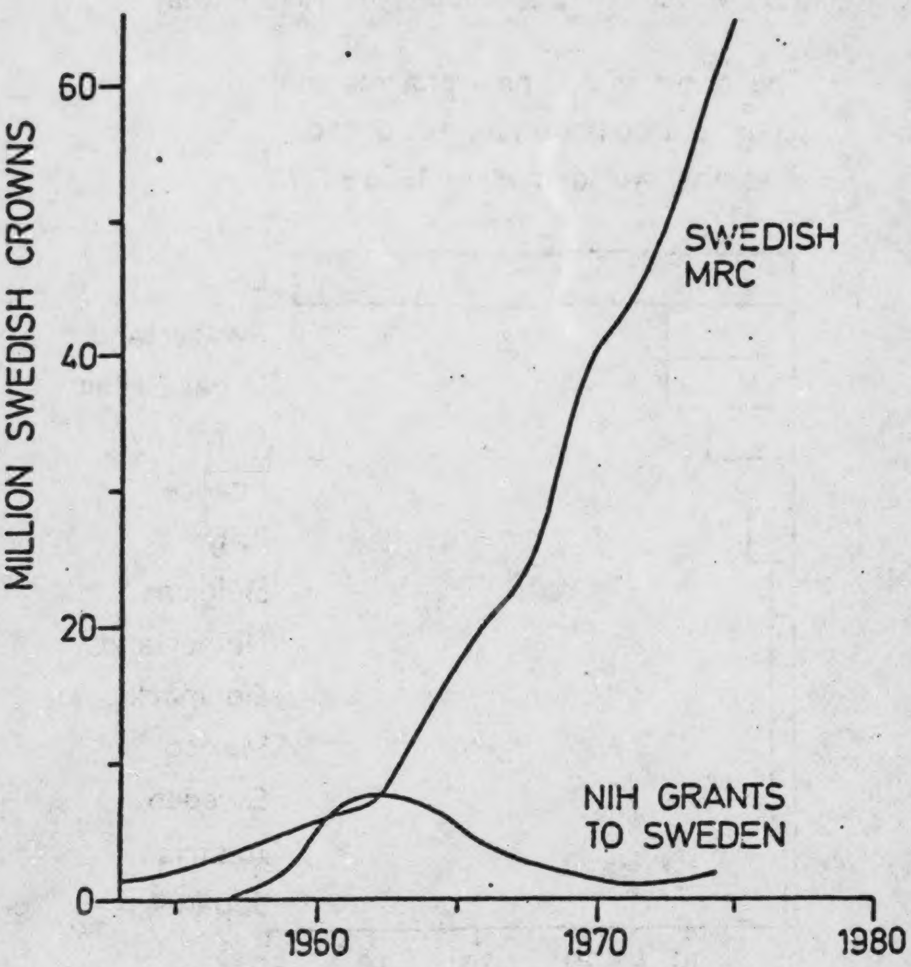


Figure 3.

I have mentioned how Swedish research was stimulated by support by a private U.S. foundation and by Federal funds from NIH.

The third interaction I will mention is related to the last decade when the World Health Organization built up three international research and training programs financed by voluntary contributions by some of its member countries that I have described more fully in a background paper.

These three research programs are focused on one, human reproduction, two, tropical diseases, and three, diarrheal diseases, the three main health problem areas of the developing countries.

The unique characteristic for the U.N. system is that it is run by leading scientists organized in scientific working groups or task forces like a research council.

The WHO staff serves as a secretariat.

About 5,000 of the leading scientists in these three crucial fields are now actively cooperating on these problems from the most fundamental research to applied field research in these truly international programs. About 25 percent of the scientists involved are from the United States.

The total annual budget is now about $55 million. Sweden has been the largest contributor in the programs of human reproduction supplying almost 50 percent of the $150 million contributed since 1972.

The net support from this program to U.S. scientists and industry has been about $11 million, of which roughly half has originated from Swedish sources, that is, Swedish taxpayers have supplied roughly an equal amount of funds to U.S. scientists that the NIH supplied to Swedish scientists in the sixties.

Actually, the support of U.S. scientists in all three programs is greater than the support from U.S. sources. I think in fact is symbolic of the growing international cooperation to tackle the grave population problems and indicates the strength of the biomedical research and development in the United States.

In the background papers I have elaborated in greater detail on these questions, especially on the important role the U.S. National Library of Medicine is playing in helping to improve the flow of information to scientists and decisionmakers in developing countries.

NLM developed the indexing system which is now adopted as the standard for WHO's efforts to register important medical information from the whole world.

The Pan American Health Organization has made an effort in this region.

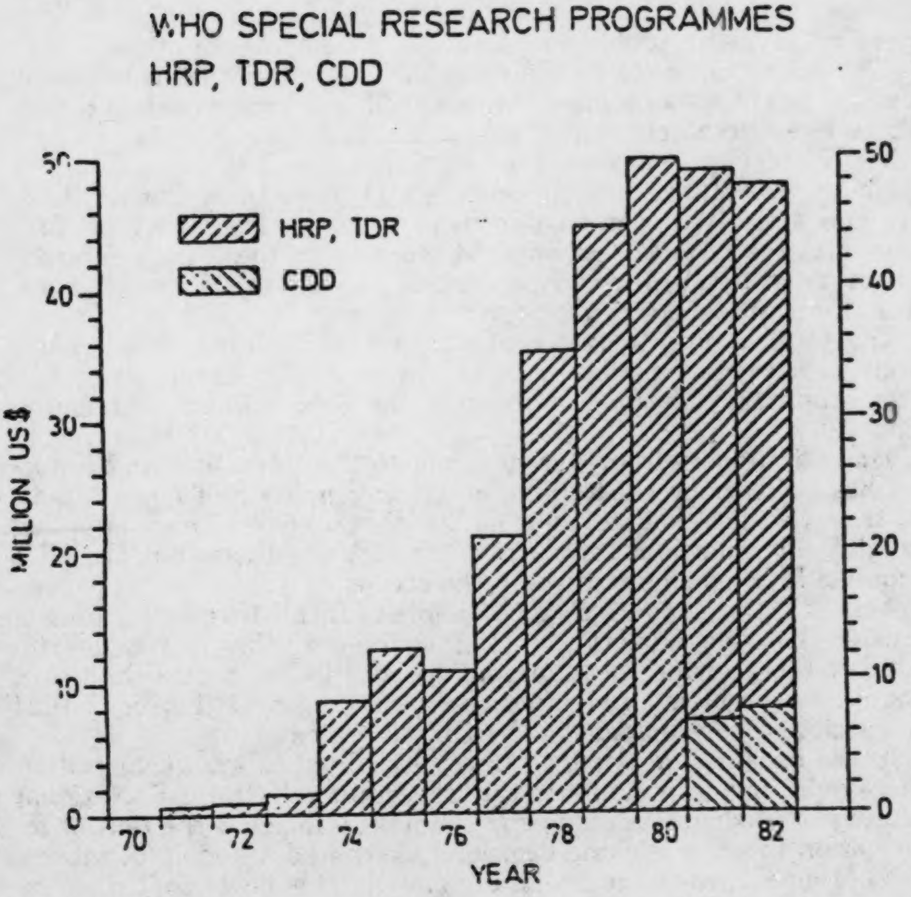


Figure 4.

Figure 4 illustrates the growth of the extra budgetary support to these three WHO programs. After a rapid increase during the past decade, the support has stabilized and now there is an indication of a decrease.

It would be tragic if the support does not continue to grow as most promising results are now beginning to emerge.

Furthermore, as more than 50 percent of the support goes to activities in developing countries, I cannot imagine a more sound and effective way to build up a North-South cooperation than this truly international research and training efforts to tackle their staggering health problems.

No nation has contributed more than the United States to support of biomedical research in other countries both through private foundations and Federal funds.

It is, therefore, of vital importance that the American experience and scientific expertise be fully utilized in these international efforts.

I believe the large U.S. investment in biomedical research and development by the Federal Government and industry during the last 30 years, and the present trend of increasing cooperation between Government, academia, and industry, may well turn out to be a decisive factor in the work to bring the health care of the developing countries to an acceptable level, a prerequisite for attaining an equilibrium of the world's population.

[The prepared statement of Dr. Bergstrom follows:]

STATEMENT OF DR. SUNE BERGSTROM, KAROLINSKA INSTITUTE, STOCKHOLM, SWEDEN

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The Institute also received a large private donation for support of medical research—probably larger than the research budget of any other medical school in Europe in the twenties.

The first important impact of the U.S. was made by the Rockefeller Foundation in supporting biomedical research in Sweden. It started in the late twenties and continued through the thirties. It consisted of approximately 90 grants and fellowships mostly in biomedical research.

Only relatively late, starting during and immediately after the war, did the governments in many countries become aware of the need for systematic planning of, and increased support for, biomedical research and development to cope with the health problems of their countries. This led to the creation of various forms of governmental research councils that have almost completely taken over the financing of biomedical research from the pioneering private foundations.

Of course the outstanding example of this development is the expansion of the federally supported National Institutes of Health and their extramural programs, which in 30 years have brought the biomedical research of the United States to preeminence in many fields. Many parameters can be used to demonstrate this fact, but I will only use one: the increase in the number of U.S. scientists who have received the Nobel Prize in physiology or medicine.

During the first two decades of this century one prize out of 18 went to a part time U.S. resident. During the last two decades 29 out of 50 went to U.S. scientists.

A similar strong position in research and development has also been achieved by the American pharmaceutical industry. An illustration of that is given in which the introduction of new drugs from 1958 to 1970 is recorded, indicating that fifty per cent of them originated from U.S. pharmaceutical industry, a parameter that possibly would show a less impressive picture today.

The Rockefeller Foundation discontinued its support of biomedical research after the war. At that time the National Institutes of Health started its unique support of international science. In the beginning of the sixties about 15 million dollars were given annually for research in other countries, the only provision being that the research was judged to be of interest and possible benefit also for the American public. Sweden was one of the countries that got much of this support and one year the support was even more than our own, newly established Medical Research Council. This international support catalyzed a lot of governmental interest in research in many European countries and when it disappeared it again stimulated the governments to replace the lost money and they then usually continue to increase the support to their research councils.

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The total annual budget is now about $55 million. Sweden has been the largest contributor in the programs of human reproduction supplying almost 50 percent of the $150 million contributed since 1972. The net support from this program to US scientists and industry has been about $11 million of which roughly half has originated from Swedish sources, i.e., Swedish tax payers have supplied roughly an equal amount of funds to U.S. scientists that the NIH supplied to Swedish scientists in the sixties.

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It would be tragic if the support does not continue to grow as most promising results are now beginning to emerge.

Furthermore, as more than 50 percent of the support goes to activities in developing countries, I cannot imagine a more sound and effective way to build up a North-South cooperation than this truly international research and training efforts to tackle their staggering health problems. No nation has contributed more than the US to support of biomedical research in other countries both through private foundations and federal funds.

It is therefore of vital importance that the American experience and scientific expertise be fully utilized in these international efforts.

I believe the large U.S. investment in biomedical research and development by the federal government and industry during the last 30 years—and the present trend of increasing cooperation between government-academia and industry—may, well turn out to be a decisive factor in the work to bring the health care of the developing countries to an acceptable level—a prerequisite for attaining an equilibrium of the world's population.

Mr. MacKay [presiding]. Thank you, Dr. Bergstrom. I am sure there will be questions from the committee members. We will question all of the witnesses or have the dialog session after all of you have spoken.

I will next call on Dr. Kenneth Wilson.

STATEMENT OF DR. KENNETH WILSON, NOBEL LAUREATE IN PHYSICS, AND JAMES A. WEEKS, PROFESSOR OF PHYSICAL SCIENCE, CORNELL UNIVERSITY, ITHACA, N.Y.

Dr. Wilson. I am very grateful to this committee for the opportunity to appear and make a statement. I would like to thank the National Science Foundation first of all for a graduate fellowship in the late fifties and then for grant support throughout most of my professional career.

I see the state of science in terms of old problems and new problems, and I will discuss old problems very briefly.

My own work was finished in 1971 so it was not affected by the funding crunch. It started out in high energy physics. The prize was for a different field—the properties of matter—and it may have applications outside of physics, for example polymer science, geology, or chemistry, but most of the applications are still to come.

The funding crunch we faced from 1968 until at least very recently has had serious consequences. There are not enough young people in our universities, and we have an aging instrumentation problem. I applaud the proposed 18 percent increase to the NSF. It will require several more such increases to bring NSF support to basic research up to full strength.

I would like to emphasize that research support from the National Science Foundation to our universities is equally important for student training because the graduate students who carry out the research are at the same time receiving advanced training. Those graduate students also help with the undergraduate teaching.

This committee is very concerned with the state of science education, and I know that you have just reported out a bill with respect to that, but I would like to say one thing: If there was a Nobel prize to be awarded for precollege science education, I would nominate Arnold Arons of the University of Washington for that award and I would recommend that it not be shared. I would hope this committee will have a chance to hear personally from Arnold Arons at some future date.[1]

Let me come to the new problems. They concern the universities in a knowledge-based economy.

In the present problems we face of international high-tech competition and fighting off the long-term structural weaknesses of our economy, we have a secret weapon. That is the U.S. universities. It is secret because this weapon is not known to the U.S. Government and it is not known to the universities themselves. But it is known to business. That is reflected in a rather peculiar circumstance.

High level executives from business are coming to universities at a rate I have never seen before. I can tell whenever one is at Cornell, because I can see the corporate jet is parked at the Tomkins County Airport. They come and they tell us they can give us very little money, but it is clear that the real reason they come is because they are looking for the universities to help them out of their present bind.

They more or less say so.

They have two problems: They come with Japan stencilled on their eyelids; and the other problem is the computer, which is creating change at a faster rate than U.S. institutions can absorb.

Japan has made fully legitimate their relationship with the computer, which in the United States is still sub rosa. In the University of Tokyo, a researcher pays one-one hundredth the cost that a university researcher at Cornell has to pay for computing.

What are the roles of the university in a computer-based society? First of all, training of engineers, executives, high level white collar people, except for the training of teachers, where as I said, you should hear Arnold Arons. There has to be retraining also because of the changes that keep taking place.

But, in a knowledge-based world, the university has new roles, roles which they have played with respect to computer technologies from the beginning. Universities demonstrate new technology before it is ready for commercial use. This is because the students can play with these machines even if they don't work very well, and the faculty can carry out their research because of the long range nature of research, even if computing jobs do not come back today every time.

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[1] Dr. Arnold B. Arons' paper "Achieving Wider Scientific Literary" appears in the appendix.

Universities pioneer new ways to use computers, to control computers, to organize computers, to teach people about computers, and they can reach out toward major long-term goals.

For example, in the area that I know best, which is the very large scientific systems called supercomputers, the major goal is to cut the time of research and development in private industry by a factor of two. The difference between universities using computers and industry using computers is play versus work. The universities are trying things. The students are learning how to use the computers. In industry a computer is always used to get something out by yesterday, and the computers aren't always very effective in that situation.

In modern society, the backbone of the university is their computer science department. Computer scientists supply the basic computer training above the level of routine business management programs. They provide computer research either by themselves or in collaboration with other users, and they train computer professionals.

The support of computer science today is pitiful. Except for the program of ARPA at four top universities, computer science suffers from being the expansion team among scientific disciplines with all that that connotates in loss of support from everybody.

I have stated that the universities are secret weapons. Can this weapon be delivered to the target?

There are problems. The first problem is technology transfer from universities to industry. The single most important need in order to increase technology transfer is an upgrade of ARPA NET communications network so it serves all scientific users in university and advanced industrial research, so that researchers in industry who need help can get on the ARPA NET, put a message saying they need help, and the right person responds to that message.

This form of technology transfer has been demonstrated on the ARPA NET. It needs to be supplied much more widely.

University people from freshmen to senior faculty need access to computers in a way that is just an extraordinary change from anything that you will find today. From computer-aided instructions, where the CDC Plato system is not available in most universities because it is too expensive, through personal computers, through internal networks, through supercomputers for scientific use.

Ultimately this will be paid for by industry because industry cannot survive without the university's help, but to help the universities make the case, they need Government help now because the only way you win university support is by demonstrating success. Theoretical arguments don't wash.

I will conclude briefly with an example. Cornell has been dealing with a small high tech company—I will call it FPS—which, during our dealing with them, has grown from $3 million in income per year to $90 million in income per year.

I started dealing with them because we bought one of their computers to do our research with, but over the last 5 years it became very clear that Cornell was helping this company in a lot of ways—not very fancy, but extremely important. The first evidence of this was that commercial customers started calling up Cornell to ask what was this computer that we got? How do we use it? Did it work well? How did it compare with the competition? We answered those phone calls, supplying knowledge. This is what the knowledge-based economy is all about. When our manager, Alec Grimison, started sending copies of his phone calls to the company, they became noticeably more responsive to our desires.

Our most important function was to lay the basis for the second product of this company, a product that will probably achieve a market in the hundreds of millions of dollars, but we got it started and the company then took it over and designed it properly to meet commercial standards.

We are now negotiating for Cornell to lay the basis for a third product for that company, a product that will have to achieve about $1 billion in sales.

We are trying to get them to give us $10 million in equipment in return for that, and most of the people in the company would give their right arm to have Cornell go ahead, but there are, of course, people that have to be brought around.

The tax credit to industry which is supposed to help this process is not working because the chief concern at this company is their pretax income, not their profits. That is what Wall Street follows.

In the end, what Cornell will have to do is create a $10 billion market for IBM, and the opening contract in that effort has already been signed.

Thank you.

[The prepared statement of Dr. Wilson follows:]

THE STATE OF U.S. SCIENCE – 1982

Prepared Statement by

Kenneth G. Wilson, James A. Weeks Professor of Physical Science
Newman Laboratory, Cornell University, Ithaca, New York 14853

submitted to the
Committee on Science and Technology
U.S. House of Representatives, February 23, 1983

Executive Summary

U.S. science has familiar problems – too few junior faculty, antiquated instrumentation. I applaud the 1984 proposed NSF budget, which begins to address these concerns. The increases proposed for research equally enhance the universities' training mission. There are less familiar but immediate problems. A national communications network serving all scientific disciplines in universities and industry is a very urgent need; it could greatly increase technology transfer to U.S. industry. Computer Science in universities gets absurdly little support except from DARPA; the NSF budget for computer science needs a major increase. Other areas of current importance include Low Temperature Physics, all of Astronomy and all of Theoretical Science. The Japanese Superspeed Computing Project should not be answered with a national crash program in the U.S.; instead there should be a major program of large scale scientific computing support for U.S. universities. This program is essential for the functioning of the commercial supercomputer market, which is currently dangerously small. More generally, all university instrumentation programs should include encouragement to university researchers to collaborate with manufacturers in generating innovations beyond the current state-of-the-art.

I wish to thank the National Science Foundation for providing me with a graduate fellowship, and for supporting my research throughout my career. I should also like to thank the House Committee on Science and Technology for supporting the National Science Foundation.

I will provide my personal impression of the present state and prospects for U.S. science. This statement is colored by my own experience — mostly in physics and centered at Cornell University.

U.S. science is strong but there are some serious problems to be addressed. As a result of the funding crunch from 1970 to date, there are too few young faculty in universities, and too much pressure on those that remain. The instrumentation for universities is too old. Science and engineering libraries have been falling behind, especially in book acquisitions, due to soaring journal subscription costs.

Last year you heard about Nobel Prizes for the discovery of lasers. Lasers are more than a billion dollar industry — they are the basis for a developing revolution in communications involving lasers and optical fibers. My own work is likely to have major applications throughout industry, but that is still in the future. However, a side effect of my more recent research is that there are ties between Cornell and a rapidly growing high-technology firm (Floating Point Systems, Inc.) Whether Floating Point Systems grows further to be a billion dollar company, or simply stagnates is likely to depend rather critically on its future interactions with Cornell. See later in this statement.

My own Nobel-Prize winning research was begun in the early 1960's and finished in 1971. I expect the long funding crunch in the 1970's to result in a lower production of U.S. Nobel awards in the future, with a corresponding reduction in benefits to our economy.

There is a renewed recognition of the importance of science in the President's 1984 budget and in the concerns expressed in Congress about science, science education and needs of the high technology economy. I applaud the proposed 18% increase in the NSF research budget. It will take several years of similar increases to restore the health of basic research. I have several comments to add. First of all, basic research, graduate training, and undergraduate teaching are inseparable in major research universities. Graduate students receive advanced training through research apprenticeship; most of the research in universities is carried out by these graduate students. The vitality of undergraduate teaching is maintained by professors communicating enthusiasm for their subjects generated by their research activities. Graduate students serving as teaching assistants both help with the undergraduate teaching and gain preparation for future careers in teaching as well as research. The size of the NSF research budget impacts all areas of university life, not just the basic research activities themselves.

There is one overwhelming need of the university and industry research community which is not in the President's budget. The need is for a computer communications network linking all scientific disciplines in universities and industry, on the model of the ARPANET of the Defense Advanced Research Projects Agency (DARPA). The ARPANET links computer scientists and electrical engineers in selected universities and defense contractors. The ARPANET has a remarkable achievement: trained users of ARPANET ask for help when they need it, instead of "reinventing the wheel".

They use the electronic mail and "electronic bulletin boards" of ARPANET for this purpose. I know of no more effective aid for technology transfer between universities and industry than to achieve one-on-one matchups of university and industry personnel as one person asks for help and the most suitable respondent replies. I have found no government agency willing to take the lead in the battle to establish a full upgrade of ARPANET, which explains why it is not already budgeted for. I would welcome assistance from Congress and the White House to give urgency to this problem. The network has special importance because it can pave the way for increased industrial support of university research.

One recent trend is that graduate students and even post-doctoral fellows in esoteric scientific disciplines are eagerly sought after by industry. Elementary particle theorists have been hired by the oil industry, notably by Schlumberger and Exxon. Their training turns out to be astonishingly helpful. Theoretical astrophysicists trained at Cornell have been hired by Kodak and General Electric, and again their astrophysics training is excellent preparation, combining application of many principles of physics with heavy use of computer simulation.

My own career illustrates that basic research cannot be targeted effectively. I began (and continue) as an elementary particle theorist, initially studying problems even my colleagues found unexciting. My Nobel Prize was awarded for research on phase transitions of matter, which came as a by-product of my research in elementary particle theory. The most important industrial applications of my work are not known yet but they are as likely to be in geology or chemistry as in physics. The lesson of this is that the U.S. basic research program should be very broad, because one cannot predict where the most important breakthroughs will take place.

There are four areas that I believe present exceptional opportunities or needs in the near future. They are: the quest for absolute zero temperature, all of astronomy, computer science, and the very wide area of theoretical science. In very low temperature physics, the discovery of new "magnetic superfluid" phases of He^3 in 1974 was a major surprise and more such surprises should await discovery. The wonders of astronomy can be extremely effective in attracting young people to science, especially with the help of populizers like Carl Sagan. In addition, modern experimental astronomy requires state-of-the-art instrumentation in areas like image processing, signal processing, and computerized "command and control" all of which have military relevance. I enclose supporting statements from Robert Richardson on low temperature physics and E. E. Salpeter on astronomy.

Computer Science in universities is under very great pressure. Undergraduate enrollments are soaring; demand for graduates are far above the supply except in the depths of a recession. Computer Science research addresses one of the most pressing productivity issues this nation faces. Meanwhile the support for computer science is at an absurdly low level, from governmental, university, or private sources, with the sole exception of a major program of DARPA. Unfortunately, DARPA (a mission agency) has its likes and dislikes and the NSF, as usual, must cover the full range of computer science activities not of interest to DARPA. Computer

Science suffers from being an "expansion team" among scientific disciplines. It came of age only in the 1970's when funds were tight; in consequence they get too little space, university support, faculty positions, or government grant support. They get a healthy increase in percentage terms in the President's 1984 NSF budget, but from too low a base level for this increase to mean much, especially considering that demands on computer science are doubling.

I will dwell more on theoretical science because it is my specialty. Theorists are learning to go beyond simple models to tackle the complexities of real life. The recent increase in hiring of theorists by industry is a consequence of this trend. In order to continue this progress, theoretical scientists must have access to scientific large scale computing far beyond current supercomputer capabilities; in fact, even the Japanese national superspeed computing project has far too conservative goals to meet U.S. theorists' needs.

My own search for large scale computing has led me into cooperation with a growing high technology firm; Floating Point Systems, Inc. (FPS). This cooperation has important implications for a U.S. response to the Japanese superspeed computing project.

Five years ago, a collaboration of several research groups (including mine) at Cornell bought the most cost-effective computer for our needs from FPS, then a tiny company. In the five years we have worked with the FPS computer, Cornell has incidentally provided major assistance to Floating Point Systems, which has grown by a factor of 25 during this period. Potential FPS customers call us up or come to Cornell to clear up confusion on what FPS equipment is good for, how it is used, the problems we have with it, etc. Cornell users demonstrate new uses for the equipment; Cornell has developed a reservoir of personnel trained in its use. Cornell has carried out major software developments for it. But our most important activity has been providing ideas for Floating Point System's second major product, the "FPS-164", which incorporates many of the features we found lacking for our needs in their first product.

Neither Cornell nor Floating Point Systems has been able to put a dollar value of Cornell's services to FPS. However, FPS personnel became noticeably more accommodating to us when the manager of the Cornell project, Alec Grimison, started sending short summaries of all phone calls he received to FPS.

It is becoming evident to both Cornell and FPS that the cooperation currently existing needs to be strengthened. FPS needs Cornell's help in opening up new markets approaching $1 billion in value. Cornell needs a major equipment upgrade — ten million dollar's worth and more. I have proposed that as part of a strengthened cooperation, FPS should provide Cornell with needed equipment over the next three years. My original suggestion was that this equipment be provided free of charge to Cornell under the new tax credit for equipment donations to universities. FPS has (so far) refused on the grounds that Wall Street has a very high growth target for their pre-tax income and they do not currently have sufficient capacity to make a major gift to Cornell and meet Wall Street's targets. Negotiations between FPS and Cornell are continuing.

My experience with Cornell-FPS cooperation has a direct bearing on an issue of national concern, namely how to preserve U.S. leadership in the broad area of "supercomputers". Supercomputers are very powerful computers for scientific applications. Newspaper and magazine articles have described a contest between Cray Research, Inc. (a company not much larger than Floating Point Systems) vs. Japan, Inc. to build the world's most powerful supercomputer. The question raised in these articles has been whether the U.S. should have a national "crash program" in order to stay ahead of Japan or leave the problem to commercial market forces.

The present supercomputer market is too small, I believe, to support an adequate commercial research and development effort in competition with Japan. I also believe that the entire U.S. industrial base needs far more supercomputing capability than they presently own, in order to increase the efficiency of U.S. industrial research and development. If U.S. industry were purchasing adequate supercomputer capacity today the supercomputer market would be large enough (in my view) to make concerns with Japan unnecessary.

I believe the main reason the supercomputer market is so small is that the entire market needs university help of the kind Cornell provides FPS. This help is not being provided. There are a number of innovative products entering the market, including new Cray and CDC supercomputers, the Denelcor "HEP", the Goodyear Aerospace "Massively Parallel Processor", the Star Technologies Star, etc. None of these machines is likely to achieve an adequate market unless they receive the same university attention that FPS products have received at Cornell, or that equipment from Amdahl, Digital Equipment, Prime, and even IBM has received in the past at other universities. Interaction between supercomputer manufacturers and universities are also needed to speed further innovations beyond the present market offerings.

In my view the main losers in the present small market are industrial users of large scale computing, present and potential. I have been trying to alert industrial leaders to this problem, and have received a sympathetic hearing from (for example) members of Exxon Corp., from the Gartner Group market research firm, and from the Business-Higher Education Forum. I have started promoting matchups between other universities and supercomputer manufacturers to complement the Cornell-FPS cooperation. I am trying to develop private support from both users like Exxon and manufacturers like Cray Research, IBM, etc. to enable universities to enter the supercomputer market forcefully. I estimate that at least one hundred million dollars per year will be needed by universities for them to enhance overall supercomputer market growth.

I have been pushing within government to get action also. Two years ago I served on the "Press" committee of the NSF; our report went into the wastebasket. Last summer I served on the Lax panel reporting to both NSF and DOD. I have followed up the Lax panel report with strong arguments for action presented to the NSF director and staff. I have participated in many workshops on the issue organized by concerned members of the Livermore and Los Alamos Laboratories.

I would welcome help from both the Congress and the White House for my efforts. A strong statement of support along with a sympathetic review of the relevant budget items would assist me in dealings with the government bureaucracy.

The basic reason for my seeking help from government as well as from private industry is the importance to the nation of the opportunities that exist in basic theoretical science research and the advanced training effort that is inseparable from this research. Theorists must be able to push to the very limits of computer technology in order to realize these opportunities, the way elementary particle experimentalists press the limits of accelerator technology.

Government support is needed in three areas. The most important is to provide the network mentioned earlier, specifically to enable matching of computer users around the country with the most cost-effective computer for their needs and to enable full utilization of expensive systems. The second need is to strengthen computer science in universities so they can help with major software issues (Cornell's ties with FPS are greatly helped by the strong computer science department at Cornell). The third need is to provide money for scientific computing, especially for operating and maintenance costs which are difficult to obtain privately.

The role of universities in the supercomputer market illustrates a more general concern. A natural role of some of the best university researchers is to help instrumentation manufacturers innovate beyond the present state-of-the-art. The lack of contact in universities with modern instrumentation is thus a multiple catastrophe for development of the U.S. high technology economy.

Appendix A

Supporting Statement — Astronomy, E. E. Salpeter

1) The next likely big U.S. groundbased astronomy facility is the VLBI (Very Long Baseline Interferometer), including approximately 10 U.S.-based new dishes. Approximately 50% of the cost will be for a Central Processor, capable of correlating the 91 baseline signals from 14 dishes, which involves a sophisticated computer engaged in analysis and "command and control." (The construction is not yet approved, but may start in FY85).
2) Optical telescopes are slowly switching from photographic emissions to CCDs (Charge Coupled Devices), which are "read out" electronically.
3) C. Bruce Tartar got a Cornell Ph.D. "Radiative Transfer in a Gas Excited by X-Rays" in 1967. Was Head, Theory Division, Livermore, sometime since then.

Mr. FUQUA. Thank you very much, Dr. Wilson.

Dr. Press, we are pleased to have you back again.

[The biographical sketch of Dr. Press follows:]

February 1983

FRANK PRESS

Frank Press was born in Brooklyn, New York in 1924. He received his undergraduate degree in physics from the City College of New York, and advanced degrees in geophysics from Columbia University in 1946 and 1949, when he joined the Columbia faculty, becoming associate professor in 1952, working in the areas of geophysics and oceanography. In 1955 Dr. Press was appointed professor of geophysics at the California Institute of Technology, and two years later became director of its Seismological Laboratory. He was named in 1965 as the head of the then Department of Geology and Geophysics at the Massachusetts Institute of Technology (MIT), which, under his leadership, expanded into planetary sciences, oceanography, interdisciplinary studies, and the joint program with the Woods Hole Oceanographic Institution, and was renamed the Department of Earth and Planetary Sciences. In 1977 he was appointed by President Carter as the President's Science Advisor and Director of the Office of Science and Technology Policy. In January, 1981, he returned to MIT where he was appointed Institute Professor, a title MIT reserves for scholars of special distinction. Dr. Press returned to Washington in July 1981 as the 19th President of the National Academy of Sciences, elected by its members to a six-year term.

Dr. Press is recognized internationally for his pioneering contributions in geophysics, oceanography, lunar and planetary sciences, and natural resource exploration, but his primary scientific activities have been in seismology and the study of the earth's deep interior. Recognizing the importance of long-period surface waves in studying the earth's structure, he developed the theory for these waves and the instrumentation to record them. Today the analyses of seismic surface waves and free oscillations are among the most powerful techniques for studying the structure and properties of the earth's crust and deep interior. Dr. Press also saw the need to develop techniques for geophysical studies of the moon and planets, using landed observatories. Author of 160 scientific papers, he is also the co-author of the textbook Earth, widely used in courses in both American and foreign universities.

Dr. Press has been a leader in major national and international projects. He helped organize and gave impetus to the International Geophysical Year, the first coordinated worldwide attempt to measure and map various geophysical phenomena, a decade-long effort that involved international explorations of Antarctica and the oceans. Mt. Press in Antarctica is named for him. Dr. Press provided leadership in research efforts on earthquake prediction in the United States, and in international cooperation with Japan, the USSR, and the People's Republic of China.

As NAS President, Dr. Press will continue a long career of public service, in addition to his distinguished scientific work. He served on the President's Science Advisory Committee during the Kennedy Administration and on the Baker and Ramo Presidential Advisory Committee during the Ford Administration. He was appointed by President Nixon to the National Science Board, which is the policy-making body of the National Science Foundation, and he also served on the Lunar and Planetary Missions Board of the National Aeronautics and Space Administration. Dr. Press participated in the bilateral science agreement negotiations with the Soviet Union, and was a member of the U.S. delegation to the nuclear test ban negotiations in Geneva and Moscow.

Major initiatives of his Washington service as OSTP Director and Science Advisor during the Carter Administration included increasing the Federal commitment to the support of basic research; the introduction of new measures to spur industrial innovation; joint research ventures involving industry, the university, and the government; and regulatory reform, particularly in improving the scientific basis of proposed regulations. Dr. Press was largely responsible for the U.S.-China scientific cooperation agreements in 1979.

Dr. Press is a member of several professional organizations, and is a former President of both the Seismological Society of America and the American Geophysical Union. He was elected to the National Academy of Sciences in 1958, the American Academy of Arts and Sciences in 1966, and the American Philosophical Society. In 1981 he was elected as a foreign member of the French Academy of Sciences, and to the Board of Trustees of both the Sloan Foundation and Rockefeller University, as well as to the membership of the Corporation of the Massachusetts Institute of Technology. He is the recipient of numerous honors, among which are the Gold Medal of the Royal Astronomical Society, the Arthur L. Day Medal of the Geological Society, the Bowie Medal of the American Geophysical Union, and in 1982, the Maurice Ewing Medal of the Society of Exploratory Geophysicists. He was awarded the Department of the Interior's Public Service Award in 1971 and NASA's Distinguished Public Service Medal in 1973. In 1982, during the 9th Annual Survey of American Leaders conducted by U.S. News and World Report, he was named the most influential man in science. Dr. Press has received 12 honorary doctoral degrees. His unique distinction lies perhaps in the dual contribution of the impact of his scientific work on the development of modern geophysics and the influence of his personal leadership in national science planning and administration.

Dr. Press is married to the former Billie Kallick of St. Louis. The Presses have two children and one grandchild.

STATEMENT OF DR. FRANK PRESS, PRESIDENT, NATIONAL ACADEMY OF SCIENCES, WASHINGTON, D.C.

Dr. PRESS. Thank you, Mr. Chairman.

May I first commend the committee for arranging these hearings.

Over the past several years they have effectively reminded Americans and the Congress of the great treasure that is American science, and they have reminded those audiences of the forces buffeting that treasure.

I imagine that every hearing has affirmed the supremacy of American science. That supremacy endures. American science is dynamic and enormously productive.

The academy has just finished, for the National Science Foundation, its third report on the 5-year outlook for science and technology.

Indeed, this report was shaped by legislation from this committee. The report examines eight areas, from psychobiology to the next generation of robots. It concludes that, "Assuming real growth in research support, the United States can expect to remain at the forefront of virtually all scientific frontiers in the 1980's and beyond."

The outlook implies the penalties of primacy; that is, the inevitable pressures that ensue by being at the frontier. However, many of the problems that the Congress, the executive branch, the academy, and the scientific community grapple with derives from just that, from our being at the top of a very slippery slope. We have to work harder at the margins, for each incremental increase in research productivity.

The corollary is that countries can catch up fairly easily, as long as their investments in research and development are high.

The fact of our primacy and the difficulties of staying there suggest several points of relevance to this hearing.

One is that the lead which the United States now enjoys can quickly be narrowed, if other countries are willing to make substantial investments in research.

The second point is that to maintain a frontier position in science and technology, we have to pay close attention to all the elements making it possible. This covers funding, education, personnel, instrumentation, the health of research institutions, and it includes a healthy economy.

The third point is that it may be to our advantage to have company on the frontiers; that we can benefit from the scientific and technological work of other countries. The big if, of course, is that of open scientific communications at both ends.

Let me briefly elaborate on these three points.

First, we should not fret too much when other countries join us at the scientific frontiers. This country has thrived on tough but fair competition. We shouldn't shrink from it now. We are rightly concerned about this country's competition in global markets for advanced technologies.

However, research is only one determinant of that capacity. There are other, much stronger, more immediate ones. These will be articulated in the research council's forthcoming report on advanced technologies and international competition.

The scientific endeavor should transcend these current frictions owing to technological competition. It is one of man's great triumphs. Science is a great binding agent, uniting men and women of all beliefs and cultures in a common quest.

However, while it is good to have company on the scientific frontiers, it is not so satisfying to see their backs. That devolves into my second point, what the United States needs to do to stay at the frontiers. In short, what we need to do to produce remarkable people like Kenneth Wilson.

Funding remains a recurring refrain. Funding here means real growth. It is a somewhat puzzling fact of science that its costs tend to rise faster than the national inflation rate. As science advances, instrumentation becomes more complex and costs more. The demands on technicians and the need for technology in support of science, such as computers, is higher. Consequently, costs increase, but so do the returns.

Against that, I am pleased with the administration's treatment of basic research in its proposed fiscal year 1984 budget. The increases for the National Science Foundation were desperately needed and, if sustained, will have an explosive effect on the range and quality of basic research done in the years ahead.

Most especially, more young investigators will be able to obtain funding, an investment that will recoup splendid benefits.

I think all those involved in this decision, especially Drs. Keyworth and Knapp, are to be commended for their foresight and appreciation of the essentiality of science to the Nation's future.

However, I am disturbed at the diminished rate of funding for the National Institutes of Health. The Institutes are a crown jewel. There is nothing comparable anywhere in the world. One can go on for hours citing the research triumphs which came out of NIH, from the research funded in its extramural programs, from the investigators who trained there, from its own laboratories.

Indeed, the academy's outlook report asserted that this may well be the era of biology; that is, an era in which innovative instrumentation from the physical sciences, such as lasers, computers, new optical and other analytical devices, is merging with fundamental insights into the nature of living cells.

It is true that the biomedical sciences en toto have enjoyed a gentle and uninterrupted growth. But we should remember the spectacular payoff from that investment. We risk that spectacular productivity by changing the pattern of funding, and we risk compounding it by cutting research grants, and the numbers of and amounts for research trainingships.

The institutions of science are as important as its substance to keeping our frontier position. This committee knows that the United States is almost alone among nations in having a major part of its basic research done in universities, and it also knows that, with the rest of the economy, both public and private universities are now under financial pressures.

Graduate tuition rates have just about tripled in the past 10 years. Many State supported universities have had revenue shortfalls owing to restrictions on State revenues. The actual costs today of educating a student in a private university are twice the tuition.

Stanford University recently announced that it would forgo $20 million in recovery of research costs. I am afraid that may be symptomatic.

Overall, the patterns of State, Federal, and private support continue to be volatile, the embedded costs of predoctoral education are rising, and some of the usual subsidies for graduate education may no longer be available.

These congeries of financial pressures may have an enduring and damaging effect on predoctoral training of scientists and engineers. Most certainly, a very welcome and beneficial recognition of the problem are the Presidential Young Investigators Awards, proposed in the administration's budget.

It seems evident that we must pay close attention to the effects of academic financing on graduate education.

Research instrumentation also remains a chronic problem. The administration's initiative in this regard is welcome. However, as I am sure Dr. Keyworth knows, the backlog is immense. One can argue that it will be difficult to keep up with the need, given the backlog and the rapidity of change. The instruments needed to reasonably equip a surface science laboratory have mushroomed enormously in just the past decade. A host of laser-based devices have entered biological research.

Computers will increase almost everyone's research productivity, and the meteorologists, chemists, physicists, need supercomputers.

One might ask, as the NRC did in a recent analysis, whether new mechanisms are needed to provide major instrumentation to research universities.

Do universities need to create institution-wide instrumentation committees, as has been suggested? Can more regional instrumentation centers be emplaced? Should instrumentation be separately budgeted from research awards?

Of course, the research universities, while essential, are not alone in keeping this country at the frontier of scientific research. Industry has a major role. So, increasingly, do the relations between universities and corporations. There are potential problems in these relationships, and we are right to be concerned.

Public support should not buffer private risks, nor should it directly enable private gain.

However, as with many things, perspective is vital. After all, the public supports basic research because it believes it to be a common good, one that will accrue in time to all people. And any mechanisms that smooth the transition from basic knowledge to economic gain ought to be looked at positively. University-industry partnerships are demonstrably such a mechanism.

Further, such relationships are not new. In fact, they antedated the involvement of the Federal Government, in basic research. The feds are the latecomers. Somewhat ironically, the suspicion of university-industry relationships tracks the suspicions of university-Federal relationships in the late thirties. If our 1930's colleagues had known about A-21, they might have been even more paranoid.

Finally, one needs to appreciate how the research system actually works to understand the explosive potential of academics talking to their corporate peers. One needs to know the peculiar ecology of the American research system.

Let me offer an example. In the early sixties, academic scientists began to probe the surfaces of solids. For example, what happens to surface electrons if bombarded with various energetic particles? They worked out ways of viewing these surfaces in enormous detail. They built their own instrumentation. They had to because it didn't exist.

That work was regarded mostly as an academic curiosity. However, in the sixties the interest in large-scale integrated circuitry began to intensify. It became important to know what exactly electrons were doing on the surfaces of solids.

At the same time, industry, for other purposes, was creating a high-vacuum technology, and that is exactly what the academic scientists needed to examine very clean surfaces.

By the late sixties, surface science exploded. Industrial interest intensified. That field is now one of the most productive in science. It has created molecular beam epitaxy, essential to the emergence of our very large scale integrated circuitry. It is transforming our understanding of how catalysts work. The economic outfalls of the rise of a true science of catalysts in the next several years will be enormous, as chemical processes become more controlled, their yields higher, and their polluting side products fewer.

What has happened in surface science mirrors the ecology of how science transforms and reshapes itself in the United States. It is a dynamic evolution of several parts, the research universities, industry, the Government, as facilitator. It is the art of science policy to maintain this dynamic.

Critical to that dynamic evolution, as the committee well knows, is a strong educational system, a system that assures that gifted and ambitious students have the resources and the opportunities of first class training in science and mathematics.

I would certainly like to commend Chairman Fuqua and his colleagues for the strong and vigorous role they have played in shaping the renewed interest of the Federal Government in the quality of science and mathematics education.

My concern is with endurance. Education is, as this committee knows, an enormously complex enterprise. It is hardly protean. It reshapes slowly. As such, it is critical that we think carefully on how to best improve the system and, most importantly, how to keep it excellent.

We need at all costs to avoid having to look back several years in the future and think of this time as Sputnik II, as again a fleeting concern with the quality of American education.

To summarize this portion of my testimony, our research remains extremely strong on any global scale, but there are penalties for primacy. It becomes ever more difficult to keep our leadership. The educational system, the strength of the institutions within which research is done, most notably the universities, and the resources available all vitally underpin our strength.

Finally, let me comment briefly on my third point related to our difficulties in staying at the scientific frontiers.

As I said earlier, we should welcome other nations gaining in research strength. For it means that their science and their generic technologies will be available to us. The Japanese work in artificial enzymes complements work in this country. Or Germans work in many fields of organic chemistry. Or French work in oceanography. Or British work in optoelectronics or radioastronomy. The quid pro quo is, of course, open scientific communication.

One can argue incessantly as to who gains most from open exchange of scientific information. It's a feckless exercise. The operative fact is that our system has no equal anywhere for rapidly exploiting new insights.

The strength of American science insures our capabilities in virtually any field. The enormous flexibility of the American research system, the academic departments, the grants open to young investigators, insures that we can quickly move into any promising scientific fields.

I think we will benefit increasingly from open scientific communication; that, with rising research strength of other nations that the net benefits will accrue to all of us. We have already benefited from open communication. We will lose a great deal by closing it off.

Mr. Chairman, in closing my remarks, I would like to call attention to a recent event that symbolizes the anticipation and excitement derived from our steps forward on the scientific frontier. Only yesterday, the New York Times carried on its front page the results of the first day of observation of the infrared astronomical satellite, launched on January 25. The results come as no surprise to the scientists, who have looked forward to this launching.

But, to the public who read this account, it must convey a sense of awe and pride in our scientific enterprise that, as the Times stated, just 1 minute of observation collected "more information on infrared emission from the large Magellanic Cloud, the nearest galaxy to our own Milky Way, than had ever been obtained in the years of looking through instruments on the ground, in balloons or high-altitude aircraft."

That event exemplifies the ever-widening prospects for scientific discovery, and so do the immense achievements of our Nobel laureates. I am pleased to join with your committee today in honoring their achievements.

[The prepared statement of Dr. Press follows:]

REMARKS

BY

FRANK PRESS, PRESIDENT

NATIONAL ACADEMY OF SCIENCES

before

THE COMMITTEE ON SCIENCE AND TECHNOLOGY

U.S. HOUSE OF REPRESENTATIVES

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9:30 a.m., Wednesday, February 23, 1983

Room 2318, Rayburn House Office Building

Thank you. May I first commend the Committee for arranging these hearings. Over the past several years, they have effectively reminded Americans, and the Congress, of the great treasure that is American science. And they have reminded those audiences of the forces buffeting that treasure.

I imagine that every hearing has affirmed the supremacy of American science. That supremacy endures. American science is dynamic and enormously productive. The Academy has just finished, for the NSF, its third report on the five-year outlook for science and technology. Indeed, this report was shaped by legislation from this Committee. The report examines eight areas, from psychobiology to the next generation of robots. And it concludes that, quote, "assuming real growth in research support, the United States can expect to remain at the forefront of virtually all scientific frontiers in the 1980's and beyond."

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However, I am disturbed at the diminished rate of funding for the National Institutes of Health. The Institutes are a crown jewel. There is nothing comparable anywhere in the world. One can go on for hours citing the research triumphs which came out of NIH--from the research funded in its extramural programs, from the investigators who trained there, from its own laboratories.

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Stanford University recently announced that it would forego $20 million in recovery of research costs. I'm afraid that may be symptomatic. Overall, the patterns of state, federal, and private support continue to be volatile, the embedded costs of pre-doctoral education are rising, and some of the usual subsidies for graduate education may no longer be available.

These congeries of financial pressures may have an enduring and damaging effect on pre-doctoral training of scientists and engineers. Most certainly, a very welcome and beneficial recognition of the problem are the Presidential Young Investigators Awards, proposed in the Administration's budget. However, I do think we need to pay close attention to the effects of academic financing on graduate education.

Research instrumentation remains a chronic problem. The Administration's initiative in this regard is welcome. However, as I'm sure Dr. Keyworth knows, the backlog is immense. One can argue that it will be difficult to keep up with the need, given the backlog and the rapidity of change. The instruments needed to reasonably equip a surface science laboratory have mushroomed enormously in just the past decade. A host of laser-based devices have entered biological research. Computers will increase almost everyone's research productivity. And the meteorologists, chemists, physicists need supercomputers.

One might ask--as the NRC did in a recent analysis--whether new mechanisms are needed to provide major instrumentation to research universities. Do universities need to create institution-wide instrumentation committees, as has been suggested? Can more regional instrumentation centers be emplaced? Should instrumentation be separately budgeted from research awards?

Of course, the research universities, while essential, are not alone in keeping this country at the frontier of scientific research. Industry has a major role. And so, increasingly, do the relations between universities and corporations. There are potential problems in these relationships. And we're right to be concerned. Public support should not buffer private risks. Nor should it directly enable private gain.

However, as with many things, perspective is vital. After all, the public supports basic research because it believes it to be a common good, one that will accrue in time to all the peoples. And any mechanisms that smooth the transition from basic knowledge to economic gain ought to be looked at positively. University-industry partnerships are demonstrably such a mechanism.

Further, such relationships are not new. In fact, they antedated the involvement of the federal government in basic research. The feds are the latecomers. Somewhat ironically, the suspicion of university-industry relationships tracks the suspicions of university-federal relationships in the late thirties. If our 1930's colleagues had known about A21, they might have been even more paranoid.

Finally, one needs to appreciate how the research system actually works to understand the explosive potential of academics talking to their corporate peers. One needs to know the peculiar ecology of the American research system.

Let me offer an example. In the early sixties, academic scientists began to probe the surfaces of solids. For example, what happens to surface electrons if bombarded with various energetic particles. They worked out ways of viewing these surfaces in enormous detail. They built their own instrumentation. They had to because it didn't exist.

That work was regarded mostly as an academic curiosity. However, in the sixties, the interest in large-scale integrated circuitry began to intensify. It became important to know what exactly electrons were doing on the surfaces of solids. At the same time, industry, for other purposes, was creating a high-vacuum technology. And that is exactly what the academic scientists needed to examine very clean surfaces.

By the late sixties, surface science exploded. Industrial interest intensified. That field is now one of the most productive in science. It has created molecular beam epitaxy, essential to the emergence of very large scale integrated circuitry. It is transforming our understanding of how catalysts work. The economic outfalls of the rise of a true science of catalysis in the next several years will be enormous--as chemical processes become more controlled, their yields higher, and their polluting side products fewer.

What has happened in surface science mirrors the ecology of how science transforms and reshapes itself in the United States. It is a dynamic evolution of several parts--the research universities, industry, the government as facilitator. It is the art of science policy to maintain that dynamic.

Critical to that dynamic evolution, as the Committee well knows, is a strong educational system; a system that assures that gifted and ambitious students have the resources and the opportunities of first class training in science and mathematics. And I would certainly like to commend Chairman Fuqua and his colleagues for the strong and vigorous role they have played in shaping the renewed interest of the federal government in the quality of science and mathematics education.

My concern is with endurance. Education is, as this Committee knows, an enormously complex enterprise. It is hardly protean. It reshapes slowly. As such, it is critical that we think carefully on how to best improve the system and, most importantly, how to keep it excellent.

We need at all costs to avoid having to look back several years in the future and think of this time as Sputnik Two--as, again, a fleeting concern with the quality of American education.

To summarize this portion of my testimony, our research remains extremely strong on any global scale. But there are penalties for primacy. It becomes ever more difficult to keep our leadership. The educational system, the strength of the institutions within which research is done--most notably the universities--and the resources available all vitally underpin our strength.

Finally, let me comment, briefly, on my third point related to our difficulties in staying at the scientific frontiers. As I said earlier, we should welcome other nations gaining in research strength. For it means that their science and their generic technologies will be available to us. The Japanese work in artificial enzymes complements work in this country. Or German work in many fields of organic chemistry. Or French work in oceanography. Or British work in optoelectronics or radioastronomy. The quid pro quo is, of course, open scientific communication.

One can argue incessantly as to who gains most from open exchange of scientific information. It's a feckless exercise. The operative fact is that our system has no equal anywhere for rapidly exploiting new insights. The strength of American science ensures our capabilities in virtually any field. The enormous flexibility of the American research system--the academic departments, the grants open to young investigators--ensures that we can quickly move into any promising scientific fields.

I think we will benefit increasingly from open scientific communication; that, with rising research strength of other nations that the net benefits will accrue to all of us. We have already benefitted from open communication. We will lose a great deal by closing it off.

Mr. Chairman, in closing my remarks, I would like to call attention to a recent event that symbolizes the anticipation and excitement derived from our steps forward on the scientific frontier. Only yesterday, the NEW YORK TIMES carried on its front page the results of the first day of observation of the Infrared Astronomical Satellite, launched on January 25. The results come as no surprise to the scientists, who have looked forward to this launching. But to the public who read this account, it must convey a sense of awe and pride in our scientific enterprise that, as the TIMES stated, just one minute of observation collected "more information on infrared emission from the Large Magellanic Cloud, the nearest galaxy to our own Milky Way, than had ever been obtained in the years of looking through instruments on the ground, in balloons or high-altitude aircraft."

That event exemplifies the ever-widening prospects for scientific discovery. And so do the immense achievements of our Nobel Laureates. I am pleased to join with your Committee today in honoring their achievements.

Mr. FUQUA. Thank you very much, Dr. Press.

As usual, we appreciate the very excellent comments and thoughts you have presented us.

Dr. Wilson, I noticed in the conclusion of your remarks you outlined three areas where Government support was needed. If I am not expanding or contracting from your remarks, they all involve some type of information system or computers?

Dr. WILSON. Yes.

Mr. FUQUA. Could you elaborate on that just briefly?

Dr. WILSON. The most important need, as I see it, from the Government, is a computer communications network that would serve all scientists. The example for this network already exists. It is called the ARPANET, which is operated by the Defense Advance Research Projects Agency for selected computer science and engineering departments and selected defense contractors of interest to ARPA.

What happens on the ARPANET is, for example, an electrical engineer wants to teach a computer architecture course. He finds that the computer for company X is something he knows nothing about, so he puts a message on the network saying, "Can somebody tell me something about this computer?"

The people who are experts on that computer reply and the reason they reply is that if they don't reply, they won't be known as experts.

This type of communication is needed between all scientific departments and advanced research establishments in universities and industry, but no agency of the Government has been willing to take the lead to push for such a network serving everybody.

The second need is in the area of computer access, which comes in many components. It is a need for huge numbers of small computers, personal computers, so that we can teach the huge freshmen and sophomore courses and make sure everybody gets computer training.

We need enormous scientific computers, the supercomputers, even though those computers will initially only be used by a few research groups each, so that we can give very advanced training in universities to people who will go out to industry and show them how to use those supercomputers in research and development in industry. There is a problem today that there aren't enough supercomputers in industry. The reason is that there are not enough people who know what they should be used for in industry. The universities have to train those people.

Does that answer your question?

Mr. **Fuqua**. I think it very well sums it up.

Dr. Bergstrom, you mentioned and had graphs of leadership goals of the United States in science. Where are the areas where Europeans are leading in science?

I am sure there are some.

Dr. **Bergstrom**. I think I can say, as Dr. Press said, that there is a frontier where we are in many fields working shoulder to shoulder really.

I could elaborate on the computer network. We have something quite unique in Stockholm. There are acute diseases that are more or less not so important any more, but the long term, chronic diseases are important. You must follow patients through many years. One and a half million inhabitants of Stockholm are on a direct line computer. Every visit to the hospital is recorded; every outpatient visit is recorded.

The length of stay, diagnosis, everything that happened to the patient is on the computer. Whenever the patient then goes to other doctors, it is recorded so they can follow through the years. I think that in the coming decades it will be invaluable for cancer, for chronic diseases, and this population will serve as guinea pigs for the world in a way because that can scarcely be done in any other place.

Mr. **Fuqua**. Dr. Press, you mentioned about the fact we should maintain a supremacy in most of the fields of science. What do you think is needed in the way of changes in our precollege and college education for science and math?

Or, do we need that to have this supremacy you referred to?

Dr. **Press**. In the area of education, we have a great deal to do in this country. In the area of precollege science, mathematics education, we are shortchanging generations of America's young people who are graduating from schools without the qualitative skills and the technical knowledge they need for jobs and for understanding. All of these things we have been talking about. Fortunately, there is a national awakening to these conditions.

I am glad that in both the Congress, and the executive branch, we have now recognized this and are moving ahead. Solutions will not be easy. They require the kinds of training and rewards for our teachers that have not been available in the past.

Universities, as I mentioned in my testimony, are in a state of disrepair in this country. They have economic and financial problems; they have an aging faculty; they have inferior equipment in the teaching laboratories. We have to address all of these conditions if we are to maintain the Nation's position of strength in science and technology.

So the agenda is a large one and without the human availability of skilled resources at all levels and in all regions of our country, I don't think we can maintain that position of strength. And without this high level of technological competence, it will be difficult to ensure the economic future of this country.

Mr. Fuqua. Thank you, sir.

Mr. Reid.

Mr. Reid. Thank you, Mr. Chairman.

Dr. Bergstrom, I was interested in a statement you made on page seven of your prepared remarks. You briefly spoke and started to elaborate but then you went on to the next prepared paragraph where you stated "It would be tragic if the support does not continue to grow as most promising results are now beginning to emerge."

You were talking about the World Health Organization. Could you tell us what the promising results are that are beginning to emerge?

Dr. Bergstrom. One of the unexpected and very promising things is in the vaccination against malaria. The malaria parasite goes through various cycles. It seems at each state now there is very promising development.

At New York University in Australia, there may be a vaccine very soon that will conquer that disease. That is one of the most important health hazards.

Furthermore, in leprosy, new vaccine developments and trials are starting very soon. That is very costly because you have to follow the patient through decades.

Mr. Reid. Dr. Wilson, I was born and raised in a little town in southern Nevada of about 250 people. I never thought I would get to meet a Nobel Prize winner. I am going to go home and tell my kids I met a Nobel Prize winner.

Could you tell me, on page 3, so I can explain to my kids, what you did? It says, "I began as an elementary particle theorist. My Nobel Prize was awarded for research on phase transitions." Tell me in layman's terms what elementary particle theorism is and what phase transition of matter is.

Dr. Wilson. Elementary particle physics has to do with what lies inside the nucleus of atoms. The question is what does matter look like on the tiniest scale we can reach with our instruments. The instruments in these cases are the big accelerators such as at Fermilab or the storage ring we have at Cornell.

What I found was that in order to understand in the mind what was going on with these experiments as one could no longer consider a single focus of a microscope. For example like 10 to the minus 13 centimeters. One had to keep changing the focus, the mental focus, in order to go to smaller and smaller distances and work out what matter looked like on all these different sizes at once.

Or, more precisely, that was what our theorists were trying to do and what I did was to figure out how we could organize our theories so that we could look at one scale at a time; first the size of the nucleus, then a tenth the size of the nucleus, then a hundredth the size of the nucleus, in turn. Then it turned out that as an exercise I needed to apply the same ideas to a problem in phase transitions. A kitchen example of a phase transition is when you boil water on top of the stove. The phase transition is simply a sudden change in the character of matter, like from water to steam.

The special case that I became concerned with is what I called a critical point, which arises for example, if you take the water and steam and put it under pressure. Then you find that there is less and less distinction between the two phases, and there is a special point at which the distinction disappears.

It turned out at that special point one had to look at the behavior on all scales from atomic sizes up to the size of the box.

I showed in that case one would start at atomic sizes, work up to twice the size, a fourth the size, eight times the size in turn; and that gave a basis for understanding a lot of the rather puzzling phenomena that were associated with that critical point.

I used the ideas that I had previously learned from looking inside the nucleus.

Where my ideas will be used most likely is in problems like the flow of oil underground where it flows in very tiny pores in the rock, and yet you have to look globally at what happens in a whole reservoir and all scales in between it.

Mr. REID. Interesting. OK.

Thank you, Mr. Chairman.

Mr. FUQUA. Thank you.

Mrs. Schneider.

Mrs. SCHNEIDER. Thank you, Mr. Chairman. I very much enjoyed the opportunity of listening to that explanation, not to mention the testimony of the other individuals that we have here. I found it most impressive.

Dr. Press, I would like to ask you, considering now that we are at wit's end attempting to determine where our budgetary priorities must be before this committee, I am concerned that there seems to be very much of an attitude—and I think perhaps you may have reflected it—that the United States does need to be at the frontier of almost every type of scientific or technological pursuit, and I understand you don't like the idea of prioritizing where we must be, but there comes a point when all of us have to do our sort of cost/benefit analysis and determine those priorities for ourselves.

I am concerned with the sort of attitude of keeping up with the Joneses. Wouldn't it be agreeable for us to say, "Well, the Swedes are further ahead in this particular area" or "The Chinese are, and why don't we lend support to them?"

I would think in fields where there are large costs for instrumentation, or various facilities, the United States might decide that either we would or would not get involved.

Do you see that as a bad kind of scientific policy for the United States?

Dr. **Press**. That question goes to the heart of the matter. I can see why you have to wrestle with it.

The United States is a great nation. It is a nation that is economically great and whose impressive strength—both in its economic structure and its national security—rests on technology.

The returns from our investments in technology have been enormous. A major fraction of the growth of our GNP over the past three decades is due to the creation of new knowledge that science produces. So it seems to me that a case can be made for the United States to argue that because of its history and its position in the world, it should stay at the forefront of most fields of science.

We are talking about what it takes to maintain that position. The basic research budget of the United States, supported by the Government, is $5 billion a year. The difference between a very healthy basic research budget and one that you might call a poverty budget—let's say that it is 10 percent. That is on the order of an additional several hundred million dollars a year for all of American science.

Compare that to other expenditures. The cost of one B-1 bomber is of that order of magnitude.

I submit that because of the tremendous impact of scientific progress on the whole of the country—the health, the economy, the security of the country—such an investment is worthy of this great nation.

Mrs. **Schneider**. You make a very good case.

I wonder if you could elaborate a little bit as to how you see us attaining this goal in addition to the expenditures for science education and retraining?

We just marked up a bill yesterday having to do with science and math and engineering education. I just wonder what your thoughts might be on what we need to do outside of putting the money in the place where we can get the most out of it?

Dr. **Press**. Education is another matter in the sense that it is our tradition in this country for education to be primarily the province of the states and the local school districts. The educational budget of the country, i.e. the local budgets of our school districts is of the order of hundreds of—well, what is it? It is many tens of billions of dollars; perhaps approaching $100 billion perhaps even more. It is one of the biggest enterprises in the country. So the Federal role can only be one of leverage, of innovations, of fixing problems, of filling gaps, of providing incentives for the proper thing to be done locally.

That is the difficulty with which you have to wrestle just what it is that the Congress can do, recognizing that the federal role is just a small fraction of the overall national budget in education.

Federal support for education is indeed an important area, but this is outside the area that I mentioned, that is the $500 million that goes primarily to research and graduate education.

Nevertheless, it is important, for unless graduating students recognize and understand science and technology, not only will we not have the scientists that are needed but we will lack a citizenry that understands these issues and a labor force with requisite skill to fill available jobs. So the matter of adequate educational training in science and mathematices also requires your attention.

You may have seen the report of the economists of the New York Stock Exchange, which evaluated Japanese productivity. In accounting for the high productivity in Japan these economists listed as the No. 1 factor the quality of precollege science and math education.

Mrs. SCHNEIDER. That certainly does add to many of the arguments that we have heard. I think our new legislation that we worked on yesterday should move us closer to attaining that goal of more highly educated students to increase our overall productivity.

One final question I have, getting more to applied research as applied to basic research. This question I ask of any one of the witnesses.

Mr. Chairman, may I have 30 more seconds, please?

Mr. FUQUA. Go ahead.

Mrs. SCHNEIDER. Thank you.

This relates to the country of China. They are establishing new priorities; they intend to quadruple their productivity, industrial and agricultural, by the year 2000.

They have various scientific goals that they have established; and one of the areas that I found very interesting was in the whole area of cancer research. Later one of our subcommittees will be holding some hearings on cancer policy. I was just curious to compare the number of dollars that are being expended for applied research into the causes and cures of cancer in a country such as China versus the dollars being spent by the National Cancer Institute here in the United States.

I am wondering if any one of you gentlemen would like to reflect on that kind of comparison? The only thing I might say is that my observation is that China appears to be far closer to a solution of dealing with cancer than the United States does in that they presented me with an atlas of where cancers of different types are located and how they have begun to diminish those numbers.

So, representing a State that has one of the highest cancer rates in the Nation and considering our greater concern now with the disposal of hazardous wastes and the health link there, I think the applied research in the cancer area is of critical importance to everyone.

I am just wondering if our feelings are that we are moving in the right direction or we should be spending more time watching what the Chinese appear to be doing in this area?

Dr. Bergstrom.

Dr. BERGSTROM. No; I think the Chinese have to look at you instead. I have seen these geographic atlases. It is very impressive, but it doesn't bring you very much closer.

I think what the International Institute is doing in collecting epidemiological surveys from all countries in the world is really the focal point for epidemiology, whereas the basic study of the course of cancer's genetic background is really being done in this country.

This last year has been fantastic in developments in that field.

Mrs. SCHNEIDER. Thank you, Mr. Chairman.

Mr. FUQUA. Mr. MacKay.

Mr. MACKAY. I would like to follow up on Dr. Wilson's comments about the need for a broader market for supercomputers. Are you suggesting that the proper role of the Federal Government would be perhaps to assist universities in the purchase of supercomputers?

Dr. WILSON. That is correct. What is particularly needed is to assist universities in the purchase of supercomputers which are just coming on the market, for example the Cray II or the Goodyear massively parallel processor, so that universities can demonstrate what those computers are good for and start the training process without which industry won't have the incentive to buy them later on.

Mr. MACKAY. In your narrative in your written presentation about the relationship between Cornell and the small computer company, that is very interesting.

I am sure that is probably the way a lot of the advances are made. How do you protect against conflict of interest in that kind of thing?

Dr. WILSON. What we do is of a very public character. We use the computer. If people call us up, we tell them facts, or our best opinion; also people come and visit. We complain to the company when something goes wrong. We often serve as a focal point for complaints from other customers.

Alec Grimison, our manager, is now president of the user's organization for the small company. In laying the basis for the company's next product, there was nothing secret about it: We simply used their first product in a way that they and their customers had not anticipated. We kept complaining to them, saying we could do this better if you had the following things in your device.

The device they came out with now has just about everything we asked for. We will continue in that same mode.

In fact, as I said, we will get support from other computer companies to do the kinds of things that will be helping this small company. This is the way real life is as opposed to the way you might think it ought to work.

Mr. MACKAY. How do you see, as a practical matter, that the Federal Government could be involved in the problem of the aging of faculty?

In other words, the fact that most faculty is tenured and you are in a steady state or declining student population time, how can government be involved in that?

Dr. WILSON. There are two things that need to happen. One is to have more research money available to the universities in a form which will lead them to hire more junior faculty, more post-doctoral research associates, more graduate students to do that research.

The other need is to promote transfer between universities and industry. You can't do this directly, but you can do it indirectly. Supporting the ARPANET is the most important thing.

When more people in industry and universities are talking to each other, one of the things that can happen is, we can break the present mode, which is that the tenured track in universities is separate from the advancement in industries.

We need to get people going back and forth—a year in the university, a year in industry—and that will make it more attractive for people to go to the university and then after the tenure decision they go to industry.

Then we wouldn't have to keep filling the tenure ranks as we keep adding assistant professors, because there would be more motion back and forth with industry.

Mr. MacKay. Thank you.

Thank you, Mr. Chairman.

Mr. Fuqua. Thank you, Mr. MacKay.

Mr. Boehlert.

Mr. Boehlert. Thank you, Mr. Chairman.

Dr. Wilson, you say there is an urgent need for more research in computer science. Where do we stand as a nation in comparison to the Japanese, for example?

Dr. Wilson. That is a difficult question for me to answer in the sense that I do not have a firsthand view of what the state is in Japan.

I have talked to one or two people, but that is not an overview.

My impression is that in pure computer science research, we are presently more in competition with places like Britain and France than we are with Japan, but that Japan is going to move very rapidly to catch up and try to move ahead of us.

Mr. Boehlert. When you say "pure," do you mean basic or applied?

Dr. Wilson. Basic.

Now, we are weak in two respects: First of all, we are weak in the basic computer science in the sense that computer science departments are just undermanned. Enrollments are soaring, demand for graduates is soaring, and there are just not enough people in the universities to handle that problem. The number of people in computer science courses double, and yet they get only one more person in the faculty.

The other weakness is in the bridge between the pure computer science and the practical use of computer science in industry.

One of the reasons that the program I am involved in at Cornell is attracting industry support despite the recession is that we have stood in the middle: employing computer science in our scientific computations, not doing pure computer science but applying it to our work.

That is explicitly why IBM signed a contract with us recently, that is, we can bridge the gap between their needs and pure computer science.

Mr. Boehlert. You are doing it very effectively at Cornell.

Thank you.

Mr. Fuqua. Thank you, Mr. Boehlert.

Mr. Valentine.

Mr. Valentine. Thank you, Mr. Chairman. I don't have any questions for these gentlemen.

I do want to express to them my apologies for arriving here late. I had some unexpected visitors, and if there are any people who are perhaps as important as Nobel Laureates, there were a few people from the Second District of North Carolina who came in to see me. So I had to spend a little time with them.

I feel much better about science in my country after having had the opportunity to listen to you gentlemen.

I want to express to you my personal appreciation for your being here. We are honored by your presence. We are proud of you. Thank you very much.

Mr. **Fuqua**. Thank you, Mr. Valentine.

Mr. McCandless.

Mr. **McCandless**. Thank you, Mr. Chairman. It has certainly been a pleasure for me to listen to the distinguished panel this morning, particularly Dr. Bergstrom from Sweden. My colleagues pretty well handled the areas of my questions. I have no further statement.

Mr. **Fuqua**. Thank you, sir.

Mr. Brown.

Mr. **Brown**. Dr. Wilson, your statement with regard to the importance of enhancing our role in computer science, expanding ARPANET and so on, is very interesting to me. This committee and specifically the Subcommittee on Science, Research and Technology, has been looking at aspects of this matter for several years without being able to come to a handle on how we could do something about it.

I will remind Dr. Press we used to needle him quite a bit in his former role about the general problems of science and technological information and how to bring that into a more coherent policy structure than we have at the present time.

Unfortunately, he never solved the problem for us when he was in that job.

As I am sure you know, computer conferencing networks and information networks of all kinds are growing apace, not as fast as the demand. I gather the physicists feel it is a very high priority to have a network similar to what I understand the chemists have and the—I was out at Encart and noted they now have two Crays and they are beginning a networking process with the Crays out there.

Of course, some of our defense laboratories have additional Crays. I am sure a lot of people who would like to have access to those Crays—we have the National Library of Medicine, the National Library of Agriculture, which have extensive storehouses of knowledge which need to be networked more broadly.

The question is, how do we grasp this total problem in some coherent way and give policy structure to it? The Air Force has just let, according to the newspapers, a contract which may run to $1 billion to network their computers around the globe, probably by satellite.

Where the Air Force goes, the Army and the Navy can't be far behind. The ones that seem to be getting left out are the civilian scientists and users.

I am at a loss to know how we can address this from a policy standpoint in the Congress in a way that will correct this imbalance.

Dr. **Wilson**. I tried to find out what the costs would be to have a major upgrade of ARPANET serving major sets of users in large universities. The figures that I have—and hopefully somebody can correct me if they are wrong—the basic cost of a connection to ARPANET to a university, is on the order of $120,000, $130,000 a year.

Mr. BROWN. Is that a cost of the computer time plus telephone charges for the linkage?

Dr. WILSON. I am told this is what ARPANET asks to be paid per year for universities to be connected.

We don't have that many really big universities. This is not a big sum. You could put that money into the NSF and tell them to copy the ARPANET, just copy everything that the ARPANET now has and it would not cost a lot of money compared to what we are now talking about.

I think Mr. Jesse Poore could give you detailed figures, if you need it.

Mr. BROWN. I have just laid that job on him.

He will come up with that very shortly.

In your wildest fantasy, have you ever imagined such a thing as a dedicated computer network perhaps with dedicated satellite links, dedicated to public service activities, in a sense a utility for data storage and computation which would serve the public interest and would provide university access, library access, other kinds of public service access that would be useful?

Dr. WILSON. The only thing I would object to in your statement is that that is a wild dream. That is something we should have in two years time from now.

Mr. BROWN. I know, but it has been dismissed as a wild dream by those who perhaps are in a position to approve the funding for such a thing.

Thank you, Mr. Chairman.

Mr. FUQUA. Thank you, Mr. Brown.

Mr. Skeen.

Mr. SKEEN. Thank you, Mr. Chairman.

I too am pleased to be here today to be a party to listening to such distinguished scientists. I congratulate all of you.

We, yesterday, as my colleague, Mrs. Schneider has mentioned, marked up a bill that would add some money to the educational system directed particularly to science and math education.

I am not always convinced that money is the total answer to the problem that we have in education, and I would like to ask from any of the three of you—including Dr. Bergstrom, as more or less an objective observer of the American educational system what you think might be a better way of disseminating information or peaking the interest of our educators in the transition of information that is, I think, garnered from the research areas and the applied science areas as well and getting that information into our educational system?

To me one of the problems we have had over a long period of time is the length of time it takes for the transition of information that has become basic to our knowledge and technology to the educational system as it is constituted in the United States.

I notice Dr. Press mentioned a moment ago that we adhere strongly to the concept that our local education systems are—and the policies developed there are controlled by people at the local level.

Sometimes I wonder if it doesn't hinder the free flow of information because we lack a basic policy of making some kinds of transitional effort in moving that information rapidly into our educational system.

Do you have any suggestions for improving that system?

Go ahead, Dr. Press. I think you ought to get another chance at my colleague, Mr. Brown.

Dr. **Press**. I think there are a number of things that could be done. It requires, I think, an education like other institutions require innovation and change. It is important for dissemination to local school districts of how to teach better, how to incorporate the newest discoveries in science into the curriculum, and all of that.

A number of ideas come to mind. I hope that these and others will be explored.

I think every school district has to know what works, what new techniques work. For example, on computer-aided teaching, or the retraining of teachers, or the enrichment of the curriculum using local industry or local universities. This is a big country. Lots of things are being tried in different communities.

If we can find out what is happening in the best way in some communities and transfer that know-how, that knowledge, to other communities, I think that could be a very effective way of improving the situation without large, enormous investments in these things.

I think most importantly there has to be a basic change in attitude of the American citizen in the importance of education, in the priority that it deserves in our country. Our teachers are underpaid, are underrewarded. When I went to school the schoolteacher was the most honored person in the community. Today he or she is looked down upon.

That kind of attitudinal change is something that I think is absolutely essential. How we accomplish it is the important question.

Mr. **Skeen**. Dr. Bergstrom.

Dr. **Bergstrom**. In Sweden, we have a much more centralized system, school system, but we have basically the same problem.

When I went to school all my science teachers had Ph. D.'s None have now. If this system is upgraded, you also get more throughflow in the universities and not this stalemate, to some extent.

I came from Australia yesterday. It is interesting that the largest income of their Academy of Sciences was from elementary textbook of biology, that they updated every second year and have made certain terrific impacts on every school district in the country.

So it is really a basic thing that must be slowly changed.

Mr. **Skeen**. Dr. Wilson.

Dr. **Wilson**. I would like to emphasize again that the person who should be answering that question is Arnold Arons of the University of Washington, but I will try to say something myself.[1]

My wife, who uses the networks, has emphasized that the networks are an incredible aid to rapid dissemination of information.

The schools should have access to computer networks, so that both the teachers and the children can get on a network and ask questions, find out what is happening.

We have to think very carefully about the allocation of our human resources. Can we put our best students simultaneously in the schools and in to the universities and in to industry as engineers and as executives?

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[1] Dr. Arnold B. Arons' paper "Achieving Wider Scientific Literacy" appears in the appendix.

I am not sure we can put them everywhere at once. I think I will end with that.

Mr. SKEEN. That gives me a very good summary of how you feel. I appreciate it very much.

Thank you very much.

Mr. FUQUA. Thank you, Mr. Skeen.

Mr. McGrath.

Mr. McGRATH. Thank you, Mr. Chairman.

Dr. Press, in your last stint as White House Director of Science and Director of the Office of Science and Technology Policy, perhaps you are in an excellent position to comment on the proposed transfer of technologies in the land-sensing and weather satellite area from government operation and control to that of the private sector?

Dr. PRESS. Well, that is a tall question.

I think I would rather think about that and catch up on all of the recent proposals that have been happening.

There are a number of questions I would ask, however. For example, if it is turned over to the private sector, what will the private sector require in front-end funding by guaranteed purchases from the U.S. Government?

Is that going to be really cheaper?

Is it possible to place a charge on weather reports across the country and how will one do that, including every farmer, every local television station and radio station? The charges could be rather heavy.

I would like to see those questions answered.

Mr. McGRATH. I see you share some of the same questions I have.

Dr. PRESS. Yes.

These are questions that require answers before one goes ahead in one direction or the other. There are certain services in the country that the public does need and in which private enterprise simply stays out, because there is no profit in it. It is necessary that somebody fill the gap and traditionally in our country it has been the government.

Everyone wants the government to limit its role as much as possible if the public can be served, alternatively, in a productive way and if private enterprise is willing to provide it in a more efficient manner.

These are examples where that works well. However, land-sensing and weather satellite technologies are still at the forefront area of R&D. We don't know what the final product will look like, and we are serving broad sectors of the country in different ways. I think we need clearer answers to these questions before we make such a decision.

Mr. McGRATH. I think you are right.

Mr. FUQUA. Thank you, Mr. McGrath.

Mr. Walgren.

Mr. WALGREN. Thank you, Mr. Chairman.

I apologize for not being here earlier. I wish I had been able to.

I was wondering, Dr. Bergstrom, if there are some direct lessons we might take from how science is organized in Europe to our benefit? Looking just through your written testimony, you do emphasize the contribution from the United States and the potential in the international area, in particular, for contribution from the United States, but thinking of just how are things progressing in Europe and whether we can learn something from the organizations that you work through, are there comments you can make in that area?

Dr. **Bergstrom**. Well, I think in Europe, with their small, fragmented, many nations we are, in some areas, like physics, we have to combine.

CERN has been very successful. In molecular biology we have a joint European center in Heidelberg. Our main problem is to have a big, open market for science. That is what the enormous advantage is here with your free communications.

I don't think we are—we are rather looking to you for the organizational aspects, but the difficult aspect, the organizational thing is, of course, to bring the developing world with us.

Mr. **Walgren**. Just one other thought. I wanted to give you a chance to repeat something I didn't hear completely. You mentioned you were in Australia and the Australian National Academy and their emphasis on elementary and secondary curriculum?

Dr. **Bergstrom**. The Australian Academy of Science voices concern, as Dr. Press said, about the level of elementary teaching, the interest in science was so low, textbooks were very bad. So the Academy itself started producing a textbook. There has been an enormous success. Every school in the country is buying it. Apparently that has already increased enormously the interest in the field and the number of people going into the universities for that.

Mr. **Walgren**. I see. I see.

Thank you very much, Mr. Chairman. I have nothing further.

Mr. **Fuqua**. Mr. Bateman, did you have any questions?

Mr. **Bateman**. Mr. Chairman, thank you.

I am sorry that I had to leave for a few minues. I have more questions. I suspect time would not permit me to ask them.

I do have a question of Dr. Wilson. You made or put significant emphasis on the need for supercomputers. In computers, if it is larger than I can carry in my pocket, it is a supercomputer. I wonder if you could define for me the parameters of what is a supercomputer?

Dr. **Wilson**. A supercomputer is variously defined. I would say it is any computer that is more powerful than the standard large business data processing computers, all the way to the most powerful computer that anybody has built. They are used mostly for scientific simulation.

Mr. **Bateman**. What would be the premier example of an existing supercomputer? A Japanese model?

Dr. **Wilson**. The premier example of the existing supercomputers is the Cray I produced by Cray Research with CDC-205 actually being more powerful, but much more recent. In about 2 years' time, they will be challenged by the Japanese companies Fujitsu and Hitachi.

Mr. **Fuqua**. Thank you, Mr. Bateman.

Dr. Bergstrom, Dr. Wilson, we are pleased and congratulate you on your recognition. We are always pleased to have our distinguished Nobel Laureate visit our committee. I regret we don't have more at the table. Maybe that will happen again.

Dr. Press, we thank you so much for the fine cooperation we get from the National Academy. We think you can tell by the questions here today that there has been a great deal of interest in where we are going, and I think you have added and contributed significantly to that.

Thank you all for your presence this morning.

[Whereupon, at 11:35 a.m., the committee proceeded to other business.]

APPENDIX

ACHIEVING WIDER SCIENTIFIC LITERACY

(By A. B. Arons, Department of Physics, FM-15, University of Washington, Seattle, Wash.)

I. Defining Objectives.

Since the focus of this essay is on paths toward, and obstacles impeding, development of "scientific literacy" or "public understanding of science", it is desirable to begin with a few specific illustrations of the meaning I assign to these terms. Such operational definitions of basic goals underlie my subsequent contentions and recommendations.

It seems to me that, to be scientifically literate, an educated adult ought to acquire at least some of the following views, perspectives, capacities, or insights:

> To recognize that scientific concepts (e.g. velocity, acceleration, force, energy, electrical charge, gravitational and inertial mass) are invented or created by acts of human intelligence and imagination and are not tangible objects accidentally discovered like a fossil, a new plant, or a particular mineral.
>
> To recognize that, to be understood and correctly used, such terms require careful operational definition, rooted in shared experience and in simpler words previously defined. To comprehend, in other words, that scientific concepts involve an idea first and a name afterwards and that understanding does not reside in the technical terms themselves.

To comprehend the distinction between observation and inference and to be able to discriminate between the two processes in a scientific context which comes under consideration.

To distinguish between the occasional role of accidental discovery in scientific investigation and the deliberate strategy of forming and testing hypotheses.

To understand the meaning of the word "theory" in the scientific domain; to have some sense, through specific examples, of how theories are formed, tested, validated, and accorded provisional acceptance. To recognize, in consequence, that the term does not refer to any and every personal opinion or unsubstantiated notion and thus, for example, to see through the pejorative creationist locution describing Evolution as "merely a theory".

To discriminate between acceptance of asserted, unverified end results, models, or conclusions on the one hand versus understanding of their basis and origin on the other; i.e. recognizing when questions such as "How do we know . . .? Why do we believe...? What is the evidence for . . .?" have been addressed, answered, and understood and when something is being taken on faith.

To understand, again through specific examples, the sense in which scientific concepts and theories are mutable and provisional rather than final and unalterable and to perceive the way in which such structures are continually refined and sharpened by processes of successive approximation.

To comprehend the limitations inherent in scientific inquiry and to be aware of the kinds of questions that are neither asked nor answered.

To develop enough basic knowledge and understanding in some area (or areas) of interest to allow intelligent reading and subsequent learning without formal instruction.

To be aware of at least a few specific instances in which scientific knowledge has had direct impact on intellectual history and one's own personal view of the nature of the universe and of the human condition within it.

To be aware of at least a few specific instances of interaction between science and society on moral, ethical, and sociological planes.

To be aware of very close analogies between certain modes of thought in natural science and in other disciplines such as history, economics, sociology, political science; e.g. forming concepts, testing hypotheses, discriminating between observation and inference, constructing models, doing hypothetico-deductive reasoning.

The preceding list is neither exhaustive nor prescriptive. It illustrates some of the insights which I believe characterize scientific literacy and which I find most college undergraduates can encompass, given time, opportunity and the willingness to exert some intellectual effort. Readers will have valid modifications, preferences, and priorities of their own. I suggest that these be interpolated and examined in the light of the following discussion.

The discussion will be confined to efforts being made through instruction in the schools, colleges, and universities. I leave to others the discussion of efforts through the media and other channels.

II. Present Condition and Necessary Alternatives

Laments regarding the state of public understanding of science are not new. Magazine articles, educational literature, pronouncements of scientific associations carry the plaint all through this century and well back into the preceding. Scientists of my own generation returned to academic work after engaging in research or serving in World War II particularly determined to help college students acquire a better sense of the nature, power, and limitations of scientific thought as well as a better understanding of the interactions between science and society. Since then the escalating impact of science and technology on moral, ethical, political, and societal problems has only continued to enhance the urgency of the educational problem and heighten the pertinence of the liberal education objective.

For years society meetings have reverberated, and pages of educational journals have been filled, with descriptions of new courses designed to lead nonscience majors to greater scientific literacy. Almost every report is accompanied by the results of "evaluations" consisting of student answers to tendentious questionaires. The answers invariably testify to how much the students loved the course, valued the learning experience, and appreciated the instructor's selfless efforts on their behalf.

With only a few exceptions, these courses and their associated texts have softly and silently vanished away to be rapidly succeeded by "more up-to- date" but essentially identical, and equally evanescent, versions, always accompanied by perpetually enthusiastic student testimonials. (I wish to make it clear that I am not deprecating student opinion as such. I question the specions use of such opinion by faculty who have failed to provide the students with an adequate frame of reference.)

These numerous atempts have had very little impact on scientific literacy. Present citizens, who were students in such courses and responded so favorably on the questionnaires, show little or no understanding of science and of its societal interactions. In retrospect, most of them say that they enjoyed the courses very much and recall nothing of what they were supposed to have learned. (It has been sardonically suggested that, this being the almost universal outcome, perhaps we should direct our efforts toward devising courses still more enjoyable and still easier to forget.) The clamor for making science a more effective component of liberal education continues unabated at a level of urgency indicative of how little the past efforts have achieved.

A principal source of failure resides in the persistent illusion that understanding of science can be achieved by purely verbal inculcation. Experience, however, is making it increasingly clear that such verbal presentations -- lecturing at large, intellectually passive groups of students and having them read text material -- leave virtually nothing permanent or significant in the student mind, much less attain the intellectual objectives defined in Section I. The procedures that have been found necessary to generate real learning in the elementary school child[1] are equally necessary for the college student who has not yet had the particular learning experience. Developing genuine understanding of concepts and theory demands intense deductive and inductive mental activity coupled with interpretation of personal observation and experience. Such activity does not take place in any but a very, very few passive listeners, but it can be enhanced, nurtured, and developed in the majority, providing it is experientially rooted and not too rapidly paced.[3,10,12,13]

Researchers in cognitive development describe two principal classes of knowledge: figurative or declarative on the one hand and operative or procedural on the other.[2] Declarative knowledge consists of knowing "facts", i.e. the earth revolves around the sun; matter is composed of discrete atoms and molecules; animals breathe in oxygen and expel carbon dioxide. Operative knowledge involves understanding of where the declarative knowledge came from. (How do we know the earth revolves around the sun? Why do we accept this view when appearances suggest the reverse? What is the evidence that the structure of matter is discrete rather than continuous? What do we mean by the terms "oxygen" and "carbon dioxide"? How do we recognize these as different substances?) and the capacity to use, apply, transform, or recognize the relevance of the declarative knowledge in new or unfamiliar situations.

Evidence is accumulating to the effect that our secondary schools and colleges are not doing a very good job of cultivating operative knowledge in any of the formal disciplines and that science is not unique in this respect, albeit the failure in science is more immediately obvious.[3,4]

Allow me some specific illustrations from personal experience. Virtually any individual will tell you that the earth and planets revolve around the sun. To many there is even nothing paradoxical about this because, unlike the ancients, few people now have occasion to watch the sky and be directly aware of the motions to be observed. If asked for the evidence and reasons for acceptance of the heliocentric system, the vast majority of individuals react only with dismay or embarrassment; some mutter something memorized and unintelligible about stellar parallax. They have nothing but declarative knowledge; they have accepted what Whitehead calls an inert end result, received from Authority; they have no understanding of the first grand synthesis provided by modern science. They are probably even less sophisticated than their medieval counterparts who would have cited the geocentric model but would have qualified it as only "saving the appearances" rather than representing final Truth. Such reactions are prototypical with respect to many other aspects of science, and, I submit, are not what we have in mind when we refer to "understanding of science."

Another example is drawn from experience with pre- and in-service elementary school teachers, a crucial population I shall have more to say about later. All these students have, somewhere in their school experience or in other circumstances, heard verbal expositions about "electrical circuits"; they have seen diagrams of electrical configurations in books and on chalkboards; they have listened to assertions of the facts and concepts of current electricity.

When these students are given a dry cell, a length of wire, and a flashlight bulb and asked to get the bulb lighted, they almost invariably start by connecting the end of the wire to one terminal of the battery and holding the bottom of the bulb to the other end of the wire, alternatively they connect the wire across the terminals of the battery and hold the bottom of the bulb to one battery terminal. They have no sense of the two-endedness of either the battery or the bulb; few of them notice that the wire gets hot when connected across the battery terminals and almost none infer anything from the observation; it takes them up to twenty minutes to half an hour to discover, by trial and error, a configuration that lights the bulb. Seven-year-old children when confronted with this situation go through exactly the same sequence at the same pace. In the absence of the synthesis of actual experience into the concept of "electrical circuit," the college students, despite the words they "know" and the assertions and descriptions they have heard, have no more understanding of the ideas involved than the seven year old approaching the phenomena de novo. Purely verbal inculcation has left essentially no trace of knowledge or understanding. Such are the outcomes of the majority of our present modes of instruction.

College courses purporting to cultivate scientific literacy in the non-science major fall into two principal classes: (1) courses which, in one quarter, one semester, or even one year, essay to give students an insight into the major achievements of a science (e.g. in physics, everything from Galileo and Newton through the laws of thermodynamics, relativity, and quantum mechanics); (2) courses which focus on some narrower topical area such as the energy crisis, spoliation of the environment, application of science to military problems, ethical and moral questions lying behind modern advances in molecular biology, philosophical questions posed by relativity and quantum mechanics, etc.

Category (1) courses have been invented and reinvented in essentially unchanged form countless times. Despite pretenses to being substantive and not subject to the pejorative characterization of "survey course," despite the always glowing student "evaluations," these courses have had so short a half-life and so little effect on the generations of students subjected to them that they are still being reinvented to fill the persisting vacuum. Youthful scientists seem to think the vacuum is there because this mode has never been tried before, and that the solution lies in presenting the material in their own particular, enthusiastic, and impeccably lucid way. Actually, the vacuum is there because the mode has been completely without educational success; its proponents, however, insist on justifying it on the grounds that the students are given a "feeling" for the content of science and the nature of modern scientific thought.

Such efforts founder--and their replications will continue to founder--because they invariably submerge students in an incomprehensible stream of technical jargon, not rooted in any experience accessible to the student, and presented much too rapidly and in far too high a volume for the assimilation of any significant understanding of ideas, concepts, or theories. The pace precludes the development of any sense of how concepts and theories originate, how they come to be validated and accepted, how they connect with experience and reveal relations among seemingly completely disparate phenomena. The pace and volume of material also preclude any meaningful reflection on the scope and limitations of scientific knowledge or of its impact on our intellectual heritage and view of man's place in the natural universe. The "stream of words" courses have not solved, and will not solve, our educational problem however handsomely illustrated the texts and however liberally salted they may be with allusions to pollution, ethics, energy crises, stellar nucleosynthesis, black holes, and Kafka.

Category (2) courses, although supposedly narrower in scope than category (1) courses, suffer from related difficulties in the way the majority seem to be implemented. One would assume that intellectual integrity demands students acquire some genuine comprehension of the scientific concepts, theories, and insights underlying the great topical problems being examined and that they not be encouraged to discourse vacuously on matters of which they have essentially no understanding.

With students who already have the requisite background, one can, of course, enter these discussions directly. But with students who have no notion what "energy" means (many regard it as a material substance) and have formed no awareness of the multiplicity of interactions leading to the restrictions embodied in the laws of thermodynamics, with students who have no basis for belief in the discreteness of the structure of matter (they have only a string of names such as "atom," "molecule," "nucleus," "electron," which have been thrown at them by assertion, without examination of any of the experiential evidence and reasoning underlying the names), with students who have no idea of what is meant by electrical charge or of the grounds on which we accept the proposition that the earth revolves around the sun, with students who are still Aristotelian in their use of teleological locutions and in their unawareness of the law of inertia, it is intellectually specious and dishonest to pursue the initial discussion without going back to the formation of the essential prior concepts. I have encountered very few students who object to doing this once they see where intellectual integrity lies and what it is that they must understand in order to talk meaningfully and intelligently about the original problem.

Such backtracking to the necessary scientific understanding, however, drastically reduces the "coverage" that can be attained. Very few such courses have, to my knowledge made the sacrifice, and the students emerge with no more understanding of scientific concepts or of the nature and limitations of scientific thought than do the victims of category (1) courses.

What is the alternative? I suggest that it is essential to back off, slow up, cover less and give students a chance to follow and absorb the development of a small number of major scientific ideas at a volume and pace that make their knowledge operative rather than declarative. Depending on time available, they might, for example, be led through one or more of the following questions:

> Why do we believe the earth revolves around the sun? In what context of concept and theory is this statement "true"?
>
> Why do we believe that matter is discrete in structure; i.e., what is the evidence for the atomic-molecular theory?
>
> What do we mean by the concept of "electrical charge"? How does the concept originate? Is "charge" a kind of substance? On what grounds do we believe there are only two kinds of electrical charge? What (hypothetical) experience would force us to conclude we had discovered a third variety?
>
> Why do we believe that atoms themselves have discrete structure on a subatomic scale? What are some simple, intelligible pieces of evidence? (Bland assertion of the existence of an entity named "electron" is not evidence of anything at all; yet much teaching is done in this style.)

> What experiences lead to and reinforce the creation of the concept "electron"? What is the evidence that such an entity is a universal constituent of matter? What is the evidence that it has subatomic mass?

In contrast, I suggest that the following enterprises, all of which I see being carried on, are essentially useless and may possibly be counterproductive:

> Students are being told about the "fascinating" particles of high energy physics, with jargon about interactions, angular momentum, mass-energy relations, quantum transitions, and the uncertainty principle, while they have yet achieved no conception of what is meant by velocity, acceleration, force, mass, energy, or electrical charge, much less of how we obtain evidence regarding the structure of matter on a scale that transcends our sense perception.
>
> Students, who are still intrinsically Aristotelians and have no significant understanding of the law of inertia, are invited to toss around phraseology about Coriolis effects in meteorology and oceanography.
>
> Students, who have no notion how to define local noon, midnight, or the north-south direction, who have no idea of the origin of the seasons or the phases of the moon (they believe the unilluminated part of the moon to be the earth's shadow), who are

unaware that the stars have a diurnal motion, are subjected to lectures on stellar nucleosynthesis, quasars, pulsars, and black holes in courses called "astronomy."

Students are conned into reading and talking about DNA, the molecular structure of genes, nerve and muscle action, while they have no idea why we believe in atoms and molecules; how we come to know anything about molecular formulas, size, or structure; what is meant operationally by "oxygen," "nitrogen," "carbon"; what is meant by "electrical charge" or "potential difference" and how we know that these concepts have anything to do with nerve action.

III. Illustrating the Nature of Scientific Thought

If one addresses ideas such as those suggested in the preceding section and does so at a pace that allows understanding of the concepts and consideration of the "How do we know . . .? Why do we believe . . .?" questions, illustrations of the character and limitations of scientific thought arise naturally and abundantly in context. They can be brought out by questioning instead of being injected artifically by assertion. Consider the following examples.

When in the "Two New Sciences", Galileo confronts the problem of describing the change in the velocity of a moving body (the idea to which we give the name "accelertion"), he points out that there are at least two alternatives: (a) We observe that the object changes its velocity from one value to another while it traverses a distance of so many cubits, and we might then elect to describe this motion by means of the number which indicates how much the velocity changed for each successive cubit of displacement: (b) the same velocity change, however, occurs over a measurable interval of time, and one might also characterize the process by the number which indicates how much the velocity changes in each successive second. Which mode of description should be adopted? The choice is not trivial.

Galileo selects the second concept: change of velocity per unit time. His objective is to create a description of "naturally accelerated" motion (free fall), and he has a deep intuitive conviction that free fall is uniformly accelerated in this sense, but not in the sense of change of velocity per cubit of displacement. On the basis of an hypothesis, an inductive guess, he selects the concept that will yield the simplest and most elegant description of free fall and proceeds to test the hypothesis by deducing consequences that can be tested by experiment.

Here are lucidly displayed several significant facets of the scientific enterprise: the roles of inductive and deductive reasoning; the fact that scientific concepts are created by acts of human intelligence and are not material objects stumbled over and described by their discoverer like a new continent or a new animal species; the fact that an element of choice may enter into the sequence and that there might be room for essentially aesthetic criteria such as elegance and simplicity.

Here also is the new and revolutionary idea of forming an a priori hypothesis and testing its mathematical predictions by experiment. The Greeks had appealed, on at least some occasions, to both observation and experiment (they adduced, for example, resistance of an inflated animal bladder to compression as experimental evidence for the corporeality of air), but they did not test the models they invented for the explanation of natural phenomena.

I do not invoke this well-known story to make claim to new or profound insights into the philosophy and history of science. I only wish to point explicitly to a set of significant ideas that college students can comprehend and appreciate--ideas that lie just below the surface in any introductory study of physical science but that students are rarely given the opportunity to discover, articulate, and savor. To discover these insights, students must have the opportunity to stand back and examine what happened, to relive some of the intellectual experience, to analyze and assess the line of thought, recognizing the elements of its logic, its strength, and its limitations.

In very few texts and courses, however, are students afforded this opportunity. The standard definitions of velocity and acceleration are asserted as though they were inevitable, rocklike formations that have existed for all time, while deference is paid to "history" by mention of the name of Galileo and by a few pompous, unsubstantiated cliches about his invention of "the Experimental Method" and his paternity, with respect to "Modern Science."

Students can indeed acquire mature and intelligent intellectual perspectives toward the methods, processes, successes, and limitations of science, but such perspectives are not automatically conveyed by training them to calculate how high a stone rises when it is thrown up into the air or how much an electron beam will be deflected by a given electrical field. Such intellectual perspectives can be developed only by coupling understanding of the scientific subject matter itself to the insights gained by standing back and explicitly examining not just the end results but what happened in terms of the "how do we know ...? why do we believe...?

questions I mentioned earlier.

Opportunities to make explicit such facets of the cultural phenomenon that is science arise at almost every turn. Consider a few further examples.

From the didactic manner in which scientific concepts are forced on students in early schooling, it is understandable that they acquire the notion that scientific terms are rigid, unchanging entities with only one absolute significance that the initiated automatically "know" and that the breathless student must acquire in one brain-twisting gulp. It comes as a revelation and a profound relief to many students if one introduces them very explicitly to the fact that scientific terms go through a sequence of evolution, redefinition, sharpening, and refinement as one starts at a crude, initial, intuitive level and, profiting from insights gained in successive applications, develops the concept to its later sophistication.

For example, the concept of "force" is legitimately introduced by connection with the primitive, intuitive, muscular sense of push or pull, but in the law of inertia, we quickly redefine it to apply to any effect that imparts an acceleration to a material object (the action of an electrically charged rod on bits of paper). We endow completely inanimate objects with the capcity to exert forces on other objects (the charged rod exerting a force on the bits of paper, the table exerting an upward force on the book that rests upon it, the Earth exerting a downward force on us [our weight] and an upward force at our feet). Following Newtom, we then extend the concept even further and create the idea that when the table exerts an upward force on the book, the book simultaneously exerts a downward force on the table. By this time we have come a very long way indeed from the original use of word "force" for an animate, muscular push or pull on another object.

Similarly, starting with the crude idea of "velocity" as a measure of how fast (as an average over a finite time interval) an object travels along a straight line, we refine this primitive notion into a concept of instantaneous velocity; we then endow the concept with additional properties of direction in space and with rate of change of both direction and magnitude.

At each stage in this sequence of evolution and redefinition, the same original word ("force" or "velocity" as the case may be) denotes a new and more sophisticated concept; its meaning has been changed in significant, intrinsic ways; it no longer denotes only the first intuitive idea to which it was applied. Modest self-consciousness about the process of definition and redefinition enormously increases the confidence of students in their own grasp of the new sequence of thought, opens their eyes to similar shifts and extensions in the subsequent generation of concepts such as "energy" and "electrical charge," and alerts them to watch for similar semantic shifts that are rarely pointed out in their study of social sciences and humanities.

In my own courses, I indicate from the first day that we will operate under the slogan "idea first and name afterwards" and that technical terms acquire meaning only through the description of shared experience in words of prior definition. When students try to exhibit their erudition (or take refuge from questioning) by name-dropping technical terms which have not been defined, I and my staff go completely blank and uncomprehending.

Students catch on to this quite quickly. They cease name dropping, and they begin to recognize when they do not understand the meaning of a term. The next thing that happens is that they drift in to tell me of instances in which they got into trouble in a psychology, or a sociology, or a political science, or an economics course by asking the instructor for the meaning of technical terms which have been flung at them in great abandon.

This repeated and reproducible feedback tells me two things: It testifies that here is an aspect of intellectual development to which many students break through relatively quickly and easily*; it also says *very* invidious things about the courses in which the negative experiences occurred.

During the 1830s and 1840s, Michael Faraday's beautiful and elegant experimental investigations of electricity and magnetism caused him to raise some very deep questions about these pehenomena, and students can be led to articulate a few of these themselves: Is there a process by which one electrically charged particle exerts a force on another? If one of the particles is suddenly displaced, does a finite time interval elapse before the force on the second changes? Does a finite time interval also elapse between the instant an electric current flows in a wire and the instant a neighboring compasss needle begins to swing in response to the magnetic effect of this current? If a finite time interval does elapse in each case, what happens in the intervening space between the interacting objects? To answer these questions, Faraday invented a model, a visualization that completely transcended any direct sense experience--the famous concept of "lines of force" that stretched, contracted, spread apart, and pulled together, propagating electric and magnetic effects through evacuated space--the concept that Clerk Maxwell subsequently elaborated into the sophisticated modern notion of "field". Almost apologetically, Faraday writes about this highly speculative model:

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* Unfortunately, this is *not* true of many other aspects of intellectual development, particularly the capacity for abstract logical reasoning. But this is another story, and, as Mortimer Snerd used to say, a long and a dirty one.[3,4]

> It is not to be supposed for a moment that speculations of this kind are useless or necessarily hurtful in natural philosophy. They should ever be held as doubtful and liable to error and to change, but they are wonderful aids in the hands of the experimentalist and mathematician; for not only are they useful in rendering the vague idea more clear for the time, giving it something like a definite shape, that it may be submitted to experiment and calculation; but they lead on by deduction and correction, to the discovery of new phenomena, and so cause an increase and advance of real physical truth, which unlike the hypothesis that led to it, becomes fundamental knowledge not subject to change.

Not only is this a beautiful description of the point and function of an heuristic model, but it simultaneously reveals a characteristic facet of the thinking of many nineteenth century scientists: They were indeed convinced that they were stockpiling "real physical truth" and "knowledge not subject to change."

After the students learn something of the conceptual revolution associated with the elements of relativity or after they have seen some of the failures of Newtonian and Maxwellian physics in the atomic realm, it is interesting to ask them to contrast with Faraday's statement the sadder and wiser one by Oppenheimer:

> We come to our new problems full of old ideas and old words, not only the inevitable words of daily life, but those which experience has shown fruitful over the years. . . We love the old words, the old imagery, and the old analogies, and we keep them for more and more unfamiliar and more and more unrecognizable things.

In the light of such perspectives, students spontaneously begin to articulate some sense of why most scientists now view scientific knowledge as mutable and provisional rather than permanent and final. They anticipate limited ranges of validity to successful theories and are fully prepared to find a deeper regression of unanswered questions behind every answered question.

In still another sequence involving models that transcend direct sense experience, one can get students to follow and examine the the evidence that led to our belief in the atomic-molecular structure of matter as well as in a structure of atoms themselves. They must be allowed to doubt with the early participants, to articulate uneasiness about the interpretation of some of the evidence--not just to be stuffed with a few disconnected and, in themselves, unconvincing arguments, followed by assertion of the end results. (After all, the original doubters were a goodly and far from foolish company.) Many illustrative gems line the way through such a sequence. Dalton, for example, in his original attempts to develop a quantitative atomic-molecular theory confronted chemical data in the form of percentage composition by weight of various compounds. The only regularity that had been noted in these data was the so-called "law of definite proportions"--a fixed percentage composition of any definite chemical compound--and even this was still a matter of some controversy and uncertainty.

Dalton's preconceptions concerning corpuscular constitution of matter led him to give particular consideration to cases in which a given pair of elements (say carbon and oxygen) form more than one compound, and it occurred to him that if 1.0 g of carbon combines with 1.3 g of oxygen in one compound, then for the same 1.0 g of carbon in the other compound one should find perhaps 2.6 or 0.65 or 3.9 g of oxygen, or some other quantity that bore a small whole number ratio to 1.3. One would expect just such simple numerical relations if compounds did indeed consist of molecules made up of small numbers of atoms of the combining elements. The data had never been examined this way; this particular orderliness lay hidden behind the unrevealing percentage compositions. Dalton looked, and the order was there; he *predicted* what is now glibly known as the "law of multiple proportions". (In many modern courses this law, if it is considered at all, is presented as though it had been known initially and provided a priori evidence for the atomic theory.) The point here, of course, is that very frequently "facts" do *not* speak for themselves. In this instance, the facts had been available for a long time, but they were not even seen until looked for through the lenses of a theory; then suddenly their presence fed back as a dramatic confirmation of the theoretical conception that revealed them.

An inverse illustration of this idea resides in the story of the famous Piltdown hoax which was exposed in the 1950s. Many paleontologists accepted the spurious "Piltdown Man" fossil with a man-like skull and an ape- like jaw because their theoretical preconceptions led them to expect an evolutionary sequence in which brain development led the way and changes in other parts of the body followed. They accepted the forgery for almost forty years, even though it was well known that it did not fit any reasonable niche in the humanoid fossil sequence. Here again facts did not speak for themselves; they were viewed through the lenses of a theory, and the theory led many astray.

In a genuinely liberal (i.e. "liberating") educational enterprise, it is essential that the broad, general characteristics of any intellectual enterprise be brought to light, but this cannot be accomplished through vague generalizations disconnected from the visceral effort which goes with mastering the subject matter. To develop scientific literacy it is essential to master at least *some* reasonable amount of subject matter in order to give meaning to the generalizations.

IV. Illustrating Connections to Intellectual History

In properly paced introductory courses, there are many ways of making students aware of the role of science in their own intellectual history:

In working in the field of elementary school science instruction I have more than once encountered the following sequence: A child asks why objects fall, and a teacher (or parent) responds, "Because of gravity." The impression is instilled in the child that a reason has been given embracing an explanation of cause and effect. There is no inkling on the part of either giver or recipient that the technical name conveys neither knowledge nor information and merely conceals ignorance. Few students, teachers, or citizens have any awareness of the history of this term: That "gravity" started as the designation of a teleological effect, a "drive" or "desire" on the part of the elements earth and water (and their mixtures) to seek the center of the earth; that Newton, explicitly eschewing knowledge of mechanism or process of interaction, made the grand surmise that, however mysteriously it might operate, the same effect which makes the apple fall binds the moon to the earth and planets to the sun; that, despite the beauty and elegance of the general Theory of Relativity, we to this day have no idea of how gravity "works".

Very few students have any conception of the revolutionary thrust of seventeenth-century science; the discarding of the notion that the heavens and heavenly bodies were made of a different substance and obeyed different natural laws from those of the terrestrial sphere; the subsumption of the entire universe under one system of humanly comprehensible natural law; the extension of the universe to infinity and the concomitant removal of the literal, sheltering heaven from close overhead. Here was a profound turning point in our intellectual history; the personal outlook of every individual toward himself and toward his place in the universe is deeply conditioned by this heritage from Galileo, Newton, and other seventeenth-century natural philosophers. An educated man should be aware of such a heritage in historical and intellectual terms, not in the mere assertion of end results.

Beautiful presentations of this story are available at undergraduate levels[5], but they are not widely used even in general education courses and make virtually no appearance at all in curricula for scientists and engineers.

Yet, if these aspects were explicitly brought out in introductory science courses, they would enormously enrich and enhance any study of the eighteenth century Enlightenment in courses in Western Civilization and would stimulate a healthy diffusion of ideas through the membranes which now divide one course from another. Students are, for example, astonished to find how many aspects of the rhetoric used by the American founding fathers in our historical documents are traceable through the deists back to Locke and Newton.[6]

As an example of a connection to literature, consider these lines by Conrad Aiken from "Morning Song of Senlin":[7]

"The earth revolves with me, yet makes no motion,
The stars pale silently in a coral sky.
In a whistling void I stand before my mirror,
Unconcerned, and tie my tie."

Aiken simultaneously invokes the law of inertia, Galilean relativity, the Newtonian cosmology, and embellishes them with a touch of irony and paradox. This a clearly modern view along the historical thread; nothing like it could possibly have been written in the sixteenth century. On another plane, it is fascinating to compare these lines with Milton's equivocation between the Ptolemaic and Copernican systems in Paradise Lost.

Another profoundly influential sequence, emanating from technology, eventually over arching and unifying all the sciences, and having pervasive impact in intellectual history is the story of the "principles of impotence". Beginning in early times with a growing qualitative recognition that Nature consipires against our "getting something for nothing", against our achieving endless supplies of matter, motion, change, or warmth without effort and cost, the eighteenth century began to quantify a few of the relevant concepts. The "nothing can be created by divine power out of nothing" of Lucretius became, in the beautiful experiments of Lavoisier, the Law of Conservation of Mass. The concepts of mechanical energy began to emerge but without awareness of their connection to heat.

The nineteenth century saw the grand synthesis of the First and Second Laws of Thermodynamics: the unification of mechanical energy and heat and the conservation of energy over all; the possible and impossible directions of spontaneous change and the trend toward equilibrium; the possibility of converting a given amount of work entirely into heat contrasted with the impossibility of converting a given amount of heat entirely into work; the subsumption of all changes in state--mechanical, chemical, thermal, electric, magnetic--under just those two laws. The quantified forms of the principles of impotence, emerging out of the technology of the industrial revolution, brought impressive and comprehensible order out of the chaos of disparate forms of change, profoundly directing and influencing the thought, for example, of social philosophers such as the French Georges Sorel[8] and historians such as the American Henry Adams.[9]

The nineteenth century had seen mass and energy as two separate, closed systems, each maintaining its own integrity of conservation. The twentieth century, through the conceptual revolution precipitated by Einstein, began to comprehend mass and energy as a unity rather than a dichotomy, just as inter-convertible as work and heat. This led to comprehension of how a radioactive material could maintain itself, apparently indefinitely, at a temperature higher than its surroundings; how the sun could keep shining for the enormous extent of geological time; and, finally, how the prodigious energy confined in the atomic nucleus could be unleashed.

The sequence leads directly to all the moral, ethical, and societal problems that precipitate out of the application of the resulting technology in peaceful industry on the one had and to warfare on the other. But the story and its influence on human society began long before Fermi and his associates constructed the first nuclear reactor in Chicago. I would hope to have students see some of this, with its ever growing intensity, in the rich perspective of intellectual history, not just in a narrow view of the immediate scientific and societal end results.

V. Variations on Theme

The preceding illustration of epistemological, philosophical, and historical aspects of science which, I submit, do infuse liberal and humanistic perspectives into any curriculum, happen to be personal favorites of mine. I present them for the purpose of being specific in my illustrations and not to advocate them above the host of other possibilities. Each teacher must select ones that appeal to him and that he can articulate to students in the most stimulating and compelling way. There is a whole array of aspects that James Conant referred to as the "tactics and strategy of science." There is the fascinating, partly scientific, partly sociological problem of validation and acceptance of scientific theories. There are the philosophical problems of positivism and the questions concerning the "reality" of entities that transcend our senses: atoms, molecules, electrons.

There are also, of course, the topical, pressing social problems that stem from the release of nuclear energy; the application of science to warfare; the possibility of synthesizing living matter and of controlling the genetic development of human beings; the problems of controlling and limiting abuse of our terrestrial environment. I have no intention of minimizing the significance of these vital problems, but I have reservations about launching into analyses or discussions of them prior to the point at which students understand the underlying scientific and technical subject matter. If they have engaged in the necessary prior study, or if the necessary background is conscientiously developed as the need arises, such discussions can be educationally fruitful and significant. If the problems are engaged without the requisite background and understanding, as is, unfortunately, sometimes done, the enterprise becomes specious, and students are misled into thinking that they have pursued deep inquiry whereas they have only dealt in vacuous generalizations, devoid of genuine thought and substance. This is not the path to literacy.

It is clearly not possoble to do everything one would like to do along these lines. It is impossible to consider every important problem, open every significant perspective. The time is long past when we could teach our students all the things they must know. It is hardly an original assertion that the only viable and realistic function of higher education is to put students on their own intellectual feet: to give them conceptual starting points and an awareness of what it means to learn and understand something so they may then continue to read, study, and learn, as need and opportunity arise, without perpetual formal instruction.

The essential criterion is that students must not end up regurgitating secondhand pronouncements about the nature and processes of the scientific enterprise without ever having articulated any such insights out of their own intellectual experience. Without at least some participation in comprehension and interpretation of scientific concepts, theories, and philosophy, secondhand statements about science have no more educational value than a commentary on poetry without a reading of the poetry, or a discussion on the philosophy of history barren of any knowledge of the history of anything.

Rather than plunging into levels of material utilizing concepts and relationships well beyond students' present comprehension, if we were to allow them the opportunity to confront science through some of the more modest insights and experiences I have tried to illustrate above, I am convinced that they would develop lasting insights far more consonant with our often postulated liberal education objectives. Such insights would contribute to the development of better educated individuals and more intellectual citizens in exactly the same way as do an awareness of history and sensibility to literature.

VI. Aspects of Implementation

Although I would encourage occasional special courses, particularly at upper division levels, devoted to specific important problems, and executed with the costly appparatus of team teaching to assure interdisciplinary perspectives, I nevertheless believe that a great deal can be accomplished in the lower division level in existing curricular structures.

What is needed is greater permeability of the walls separating courses in the sciences, the humanities, and the social sciences. In the illustrations I have given above, I have tried to show how teachers of the sciences could enhance the liberal content of their own courses. What is required is a deliberate effort on the part of a teacher to become more literate and more articulate about historical, philosophical, epistemological, or societal overtones than he was prepared to be in his own education. Materials to this end are readily available both for teachers and for students, and only a little ingenuity is required to devise questions, homework problems, and paper assignments which lead students to confront ideas that transcend the sterile end results of particular modes of calculation or problem solving.

It is true that, in our present science courses, infusion of such material would force us to back away from the already insane volume and pace of coverage which is imposed on our willing and uncritical students. I have long argued, in other places, that we are crushing our students into the flatness of equation grinding automatons and forcing them into blind memorization of problem solving procedures. We do not even give them a chance to begin to understand what understanding really means. Were we to require that they understand concepts and lines of reasoning within the perspectives I have outlined, we would be setting far higher intellectual standards and demanding far higher performance than we now attain with all our vaunted "coverage". This would not be a "watering down"; it would be a raising up. I know at first hand that students can and do respond to such demand.

It is futile simply to exhort the students regarding the importance of liberal education and to give them nothing but ringing platitudes. We must be sufficiently knowledgeable and sufficiently concerned to bring before them compelling and significant instances of intellectual, moral, or aesthetic experience. To this end, the instructor of science or engineering must exhibit his own capacity to deal with such dimensions, otherwise the exhortation is hypocritical. How can we demand that the students do something we do not do ourselves?

But the burden is not on the technical instructors alone. The walls must be permeable in the other direction also. Instructors in the humanities must cease running from "hard science", as most of them probably did during their undergraduate careers. They must bring themselves to master at least a few of the "how do we know . . .? why do we believe . . .? questions I mentioned earlier. They must invoke scientific subject matter and consequences in a knowledgeable way in their own courses, e.g. the influence of Newton should be seriously discussed (not casually and superficially) in any history course dealing with the eighteenth century. The humanist and the social scientist must set an example for the students in the same way I demand of my technical and scientific colleagues. How can we expect the students to cease running from anything which makes them feel intellectually insecure if we persist in running ourselves?

I labor under no illusion that all this is easily accomplished, but I see virtually no really effective alternatives if we are to achieve some fraction of the grandiose objectives to which everyone so glibly renders lip service. I myself did not receive this kind of education as an engineering undergraduate. If I have survived that education intellectually, I have done so by climbing out of the pit by my own hand-and-toe holds in the subsequent years, and I labor under all the wounds and severe limitations that constrain one in such circumstances. I have found the effort, however, highly rewarding.

VII. The Problem of Cognitive Development

If we accept the premise that our liberal education objectives entail thinking, reasoning, and understanding on the part of the students, it is then essential that we take into account the empirical results of current studies of cognitive development. Such studies,[2,3,4,10] usually based on administration of two or more of the now classical Piagetian tasks, are showing with remarkable reproducibility, that no more than about 25% of the cross section of college students have developed the capacity for abstract logical reasoning at the level of these rudimentary tasks. It also emerges that up to 50% of the students are still using predominately concrete patterns of reasoning, while the remaining 25% seems to be somewhere in transition, exhibiting only partial success in the formal reasoning tasks.

Students do have intellects capable of development beyond the point at which the tests now find them[10,12,13,14]. Such development, however, is necessarily based on practice and experience with important modes or reasoning - repetitive practice, leading, in Piaget's terminology, to accommodation and equilibration. Most college students are very much in need of practice in the following modes, and practice must include the opportunity to detect and correct error: (1) forming and understanding simple propositional statements and one- or two-step syllogistic statements; (2) recognizing when they do not understand something they have read and identifying the point on which the lack of understanding hinges (3) doing elementary hypothetic-deductive reasoning (i.e., visualizing in the abstract the possible consequence of various changes imposed on a system); (4) recognizing the circumstances under which cause-and-effect relations can or cannot be established (i.e., having grasp of the logic of control of variables); (5) doing elementary correlational reasoning; (6) doing arithmetical reasoning utilizing ratio and division, including simple scaling of areas, volumes, or other commonly encountered variables; (7) translating symbols into words and words into symbols (as in the verbal interpretation of graphs or other visual presentations and the translation of verbal statements into graphs or arithmetical operations).

As pointed out earlier, the pace and volume of material thrust of students in the majority of liberal education science courses are such as to preclude the exercise of the time consuming operations of thinking, reasoning, and understanding. The majority of students are thus forced into blind memorization, and they eventually come to see all "knowledge" and "understanding" as the juxtaposition of memorized names and phrases. They are not held to and tested on the reasoning; they are tested only on the memorizable end results. In these circumstances, there is essentially no hope of developing insights and understanding which characterize genuine scientific literacy--or, for that matter, literacy in any field requiring abstract logical reasoning.

If we really wish to succeed in our liberal education objectives, it is essential to show more respect for the intellects of the students by assuming that these intellects are capable of development and use. Then it is necessary to provide opportunity for thinking, reasoning, and intellectual development at a pace and level that students can assimilate. Genuine understanding of a limited range of fundamental subject matter would testify to far higher intellectual standards and requirements than regurgitation of memorized jargon with respect to advanced or topical subjects.

VIII. The Problem of Teacher Education

It is not difficult to see that far and away the highest leverage and the highest potential for improvement of public understanding of the subject matter, methods, limitations, and social impact of science reside in the elementary and intermediate schools. Given sound beginnings, with genuine understanding of basic concepts at this level, subsequent levels of instruction would be enormously facilitated. Students might even come to college and university with levels of reasoning skill and subject matter background such they could penetrate aspects of modern science which are now hopelessly unintelligible. With such improved background, even our mass production system of lecturing to large classes might be considerably more effective than it is in present circumstances.

Such progress, via improvement in teaching at elementary and secondary levels, is impeded at the present time not by lack of adequate curricular materials but by inadequacy in the education of teachers.

It is unlikely that any curricular materials, however high their potential for cultivating thinking, reasoning, learning and understanding, will ever be "teacher proof". It is always possible for a teacher to negate the intent of the materials by attitude, by invidious comment, and, most significantly, by what he chooses to test for. The real intellectual values of a course are established by tests rather than by texts. If improved curricular materials are to be successfully implemented, we must have teachers who are secure in the use of the materials. "Security" in this context means both thorough understanding of the subject matter content and thorough understanding of the underlying pedagogical intent and design. The latter understanding is impossible without the former.

For example, lack of widespread success in implementation of the existing fine elementary school science curricula[1] resides not in intrinsic weakness of the materials but in the fact that college science preparation has failed to provide elementary school teachers with the knowledge and understanding necessary for effective use and implementation. In our work with both pre- and in-service elementary teachers at the University of Washington we have established that the two groups are initially indistinguishable: the majority use concrete rather than formal patterns of reasoning; they cannot do arithmetical reasoning involving division (i.e., very few can do the word problems of 5th and 6th grade arithmetic); they do not control variables; they cannot visualize possible outcomes of changes imposed on a system; their "knowledge" of science resides exclusively in memorized names and technical terms with which they have not associated sufficient operational meaning to be able to reason with them in any specific instance.

In other words, our elementary school teachers, if they have had any physical science at all, have had courses of the variety about which I waxed critical in Section II. Such courses do not help the future teacher exercise patterns of reasoning; they do not engender understanding of the subject matter. The future teacher is left with a half-remembered string of words such as nuclei, lasers, strange particles, angular momentum, and black holes and barren of understanding of the concept of density, of floating and sinking, of the law of inertia, of the distinction between heat and temperature, of the origin of the phases of the moon or the annual motion of the sun, of the notion of electric current in the simplest resistive circuit, or of the most prevalent everyday phenomena of light or of mechanical wave motion. The good elementary school science curricula wisely pursue the realms of everyday experience rather than esoteric vocabularies of modern physics, and the teachers find themselves at exactly the same level of initial knowledge as the children. I have heard honest and perceptive teachers volunteer this remark about their present condition in exactly these terms.

In our investigations, we have time and again confirmed the empirical observation that adults (pre- and in-service elementary teachers) acquire the abstract reasoning patterns and the conceptual understanding conveyed in the elementary science curricula only by passing through exactly the same obstacles, hurdles, and difficulties as are experienced by the children. Furthermore, they progress through any such learning sequence at no more rapid, and frequently at a slower pace, than do the children. A major fraction of the effort expended on short workshops intended to help in-service teachers implement the new elementary curricula has been completely wasted because of the failure to recognize the necessary time element. Their college background has left the vast majority of the teachers at the same point as their pupils. It turns out to be illusory to hope that brief indoctrination about the "philosophy of the program" and subsequent immersion in the materials will induce understanding of the content. We have found that only slow and patient traversal of both abstract reasoning patterns and of subject matter will give the teacher the kind of security that leads to successful implementation.[11,12,13,14] In the meantime, in the absence of any change in our college courses and curricula, we continue, and will continue, to produce elementary, intermediate, and secondary school teachers who are in need of remediation the instant they graduate. But this is not inevitable. We have satisfied ourselves, in our own investigations, that the large majority of pre- and in-service teachers do develop the requisite competence given the proper opportunity.

A very common manifestation at the present time of the inadequacy of the subject mater background of elementary school teachers resides in their reaction to the better curricular materials which are available for their use. In some instances, the materials simply stay locked up in closets and are not used while the teachers, if they are obligated to teach science, proceed to lecture out of the standard older texts. In other instances, teachers, insecure in the face of the new materials, finding them "too difficult" for the children, and unaware that the trouble lies in their own lack of understanding, band together and direct their energies and their good intentions to writing materials of their own. The result is invariably trash, full of errors, misconceptions, and misstatements, with probably negative educational value. (It must be reemphasized that the existing excellent elementary school materials referred to previously[1] were developed by mature and highly competent scientists who had the necessary perspectives and understanding.)

Research on teaching and learning may give us better instructional materials, but these materials will never have a really widespread impact in the schools unless we produce teachers who can implement them. This is a major problem, and it remains rooted at the college-university level. Accusations and recriminations made against elementary and secondary teachers are, for the most part, unwarranted and unjust: "The fault, dear Brutus, is not in our stars..."

Besides understanding of subject matter and exercise in use of formal patterns of reasoning, one other aspect of teacher education that deserves explicit attention is that of behavior in the classroom. The good new science curricula are organized not around lecturing and inculcation by the teacher but around exploration, trying and erring, talking and listening, arguing and explaining among the students themselves. (There is evidence that when competently implemented, the science materials simultaneously enhance reading comprehension and arithmetical reasoning capacities in the children.[15]) In many instances, when children are following an erroneous course, it is important that a teacher direct their attention to inconsistencies or contradictions inherent in what they are doing and guide them to revision or correction without immediate assertion of a "right answer". Such behavior takes confidence, security, and command of content and reasoining on the part of the teacher--lecturing and asserting the right answer are much easier and are the refuge of the insecure. But even with adequate subject matter background, it is asking too much to expect such sophisticated behavior of a young person thrown into a new classroom. The pre-service teacher must have help in the way of both prior example and instruction. Many researchers in this country and abroad consistently show that teachers tend to teach as they have been taught. If we do nothing but lecture at our pre-service teachers, they will lecture in their own classrooms regardless of the indoctrination they may be given (also by lecturing) in their "methods" courses in the departments of education.

It is essential that courses be set aside for future teachers which are taught in small classes in exactly the way we wish to have the elementary science curricula implemented. The science course then becomes simultaneously a methods course, as it should be. Given teacher education of this kind, we would begin to hope for a shift in the schools that would have a highly significant impact on the feedback to college level.

IX. A Role for the Computer

One outcome of current research, and observation, over a wide range of different courses, which has been made repeatedly in our group at the University of Washington is that many students do not break through to command of a particular concept or sequence of reasoning unless they can be reached in a one-on-one dialog.[13,16] This is particularly true of pre- and in-service elementary and secondary teachers. Specific examples are: arithematical reasoning using division; distinction between velocity and acceleration; interpreting position-time and velocity-time graphs in words and in motions executed by one's own hand; distinction between heat and temperature; forming and using the model for origin of phases of the moon (i.e., dealing successfully with questions such as "would you expect to see a full moon rising at midnight? why or why not?"); forming and using the model of current and concept of resistance so as to predict brightness changes that would result from alterations (shorts, removal or insertion of other bulbs) imposed on simple circuits composed of batteries and flashlight bulbs.

Such one-on-one dialogs with a single student can easily take as long as 20 to 30 minutes or more. It is hardly possible to do this with a sufficient number of students even in small classes, and it is completely out of the question in large ones. One might adopt the view that student who cannot break through to mastery of such simple and basic concepts or reasoning modes do not deserve additional effort on the part of the staff and do not belong in science courses.

Enlightened self interest, however, if not a broader objective, dictates a less callous view. Among the students who fail or who simply disappear from our courses (or who never enroll in the first place because of their deep fear and insecurity) and who could be saved by one-on-one help at strategic points, are many potentially promising minority students as well as most of our future elementary school teachers, not to speak of many others.

Here is a point at which modern technology can be of some assistance. The coming of age of the stand-along microcomputers with graphic capability offers the prospect of making one-on-one instructional dialog[17] practicable in spite of numbers. The problem becomes one of writing effective dialogs that pull students over the early, most severe obstacles and help put them on the way toward further learning, with decreasing dependence on such tutorial assistance.

Writing of effective dialogs will, of necessity, lean heavily on the results of researches in cognitive development. Not only must a skillful author have a broad awareness of what is being learned in general about cognitive development and patterns of logical reasoning, he must also draw heavily on the detailed, concept-by-concept student protocols. We ourselves very rarely make correct conjectures about the students' preconceptions, misconceptions, and linguistic difficulties. Yet, for a really good computer dialog, the most important and most difficult provisions an author must make are the ones that lead a student to rectify *incorrect* responses; it is easy to take care of the correct ones. The exercise of writing computer dialogs has an additional, valuable, secondary effect on the authors themselves. Time and again, after the intensive intellectual exercise of outlining such dialogs in a workshop, I have seen veteran teachers lean back with a traumatized air and say something to the effect that "I will certainly never teach *this* subject matter the same way again. I cannot see how I ever accepted the presentation I have been using. It is full of holes that must have confused the students."

learning from past experience

With the present resurgence of concern about education of scientists and engineers and about public understanding of science and technology, some individuals are pointing to what they regard as the "failure" of the curriculum development efforts of the fifties and sixties and are advocating a new round of preparation of text materials, hoping that this time the materials will be "better" and "more effective." It seems to me that this is a fallacious and forlorn hope. Although many of the existing curricular materials can certainly be improved in pedagogical quality, this alone will not overcome the real obstacles and underlying problems. Curricular materials, however skilfull and imaginative, cannot "teach themselves."

I do not consider the science curriculum writing of the fifties and sixties to have been a failure. At the time these efforts were undertaken, principally under the stimulus provided by the National Science Foundation, new text materials, particularly ones rooted in laboratory and observational experience were very badly needed. Existing texts were obsolete, full of errors and misstatements, and intellectually sterile. They had been copied and recopied for several generations by authors who themselves did not have adequate and up to date knowledge of the subject matter.

In the heady, evangelistic atmosphere of two decades ago, leaders in the various scientific and technical fields brought imaginative insight, current perspectives, and correct logical underpinnings to the new materials. It is true that the materials produced were not uniformly high in instructional quality. Some of these materials were too rapidly paced for the age groups for which they were intended. Some started by asserting end results of sophisticated developments in other scientific fields, required the students to memorize these end results without examination of any underlying "how do we know....? why do we believe.....?" questions, and proceeded to drown the students in incomprehensible consequences of the initial, unsupported assertions. Some of the curriculum developers, not having the benefit of more recent insights into the actual levels of capacity of different age groups for abstract logical reasoning [4] , went off into abstractions completely beyond the grasp of the pupils they were ostensibly addressing (and of many teachers as well.) Mathematics, in particular, suffered from such misdirection.

However, despite some of the misplaced effort, a significant number of excellent curricula were developed. In my opinion the best ones are among those designed for elementary school [1] . In these materials, children start from scratch with no presupposition concerning prior "knowledge" of technical terms. Ideas come first and names afterward. Concepts are synthesized out of observational experience rather than being received through didactic presentation. Reasoning starts at concrete levels and, providing it is under the guidance of a competent teacher, gradually proceeds toward the abstract. Repeated intellectual experiences of this kind stimulate the emergence of abstract reasoning capacity and enhance its subsequent development. Some sound and potentially effective materials were also developed for junior high school and high school levels. In most instances, these materials are mismatched to the particular age level the developers had in mind, but they are usually well suited to students one, two, or three years older.

My point is that a substantial body of interesting, imaginative, and educationally sound material was developed despite some mistakes. These materials are not obsolete or out of date. Their adoption and implementation has indeed been disappointing, but I contend that the "failure" which is adduced in this connection does not stem from deficiencies in the quality or character of the materials themselves. The failure stems from external causes not intrinsic to the materials. Although the better of the existing curricula are surely not the last word in educational sophistication, and although improvements are certainly possible in the light of improving insights into aspects of cognitive development, I am convinced that a new generation of materials would suffer exactly the same failure in adoption and implementation from the same extrinsic causes.

There were two principal causes for the failure to which we keep alluding. One cause was inadequacy of logistic support, particularly in elementary and junior high school, for teachers venturesome enough to try the new curricula. Hands-on, laboratory oriented materials require continual maintainance and re-supply. Busy and overloaded teachers need sustained support in using such materials; they cannot take care of the logistics in addition to all the other duties they are expected to discharge. Although they might make the extra effort in the initial wave of enthusiasm (and many of them did), it is impossible to sustain over long periods of time. The necessary logistic support was rarely strong even at the beginning of adoptions, and it rapidly melted away altogether in the seventies with growing financial pressures on the schools.

Thus, one formidable obstacle which must be overcome at all levels in the schools is that of logistic support. It is illusory to suppose that widespread scientific literacy will ever be successfully cultivated through instructional materials based on purely verbal inculcation. The necessary understanding, reasoning, and mastery of concepts and ideas will evolve, in the great majority of ordinary individuals, only from concrete observational experience. It is true that some gifted individuals do break through to scientific understanding, and to abstract reasoning in general, without such concrete help. But this small fraction of the population has always broken through, perhaps with some delay, regardless of the circumstances. We are indeed fortunate that this is the case, for otherwise scientific literacy would be far lower than it actually is. Our reiterated goal, however, is a large increase in the literate fraction. This goal will not be attained without providing the majority of young students with hands-on experience and with sustained guidance in carrying reasoning from the concrete to the abstract.

The second, and most significant, cause of failure in adoption and implementation of the better curricular materials lay in what happened in the re-training of teachers. Huge amounts of money and effort were poured into summer institutes and academic year programs, most of them under the direction of college and university faculty members. A few of these programs were beneficial because the staff recognized that the teachers had developed little genuine understanding of scientific subject matter in their previous school and college courses and were very nearly at the same level of conceptual development as their pupils. Accordingly, it was realized that the teachers must be guided slowly and carefully through the intellectual experiences they were subsequently to convey in their own classrooms. In the majority of teacher training programs, however, this necessity was not understood or appreciated. It was falsely assumed that the teachers, elementary through high school level, really understood the very elementary science they were to be teaching (or that they would quickly learn it, along with the students, from the marvelously lucid new materials.) In the summer institutes and other programs, the teachers were thus given lectures about the "educational philosophy" of the materials, the substance of which they still did not comprehend. Or, they were given more advanced subject matter, also totally incomprehensible, in order to extend their perspectives and knowledge of most recent progress in the field. Or, in the largest number of cases, they were simply given more of the same rapidly paced, irrelevant, and unintelligible college courses that had had no visible intellectual effect in the past. In such instances, the teachers were no better able to handle the new curricular materials than they were before coming to the training program. It was not their fault that they had no awareness of this deficiency and that, in subsequent, disappointing classroom experiences with the new materials, they ascribed the trouble to the difficulty of the materials rather than to their own inadequate understanding. (Let me hasten to say that I am not tarring all teachers with this brush. I know personally, and I continually hear about, superlatively competent teachers at every level. These are far too small a fraction, however, to make for solution of the problem.)

If we wish to produce widespread improvement in public understanding of science, we will have to take significant steps toward mitigating the two principal causes of our previous failure. The problems are very difficult but not intrinsically insoluble; the remedies are necessarily fairly costly, and by far the most difficult part of the problem is conveying comprehension of it to our college and university faculties. If they do the same thing over again in teacher training, there will be no progress.

Curricular materials, however fine, will never achieve our goals entirely by themselves. They may improve things for the especially gifted, but they will not solve the problem for the vast and perfectly respectable majority. Unless the essential underpinnings I have pointed out are provided, tinkering with new curricular materials will again absorb huge amounts of money and effort and will leave us exactly where we are at the present time. We will have a new crop of complaints about failure and inadequacy of the materials and a revived demand for another wave of needless curricular development. Attainment of wider scientific literacy will keep receding into the infinite educational perspective.

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